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(B) denotes Book Review

The influence of phytoplankton pigments on the colour of sea water

CHARLES S. YENTSCH

(*Received* 15 *July* 1959)

Ab tract—By summing the absorbency of phytoplankton pigments with that of pure water, the absorption of the blue portion of the spectrum is markedly increased. As the concentration of phytoplankton pigments increases, the diminution of blue light gradually shifts the wave length of maximum transmission toward the green. At the concentration of phytoplankton pigments normally found in the open ocean, the red chlorophyll band has little influence on water colour.

Inadequacies in present methods for detection of absorption bands in natural waters is attributed to wide band widths of filters used in submarine photometers. Poor spectral curves applicable to colour analysis in particulate systems are obtained by conventional spectrophotometric techniques because a large portion of the scattered light never reaches the photo-detector. Improvements for spectral analysis are suggested.

INTRODUCTION

THE clearest ocean waters are deep blue, those near coasts usually are green, while many inshore estuarine waters may be brown or red, the colour generally varying with the proximity of sources of land run-off. These differences in colour can be attributed to variations in the magnitude of scattering and absorption of daylight.

KALLE (1937, 1938, 1939) and JERLOV (1951a, 1951b, 1953, 1955) have concluded, consistent with earlier theories of ocean water colour, that the blue colour of the clearest oceans arises from the selective scattering of short wave lengths by water molecules and small particles, while the change from blue to the green of coastal waters is the result of selective absorption by dissolved yellow materials in the water.

Recently, ATKINS and POOLE (1958) and YENTSCH and RYTHER (1959) have indicated the importance of absorption in the blue regions of the spectrum by the photosynthetic pigments of phytoplankton. The present report is an attempt to evaluate the effects of this absorbency on the colour of natural waters.

COMPARATIVE TRANSPARENCY OF PURE AND NATURAL OCEAN WATERS AND THEORIES WITH REGARD TO COLOUR

A number of investigators have measured the transmission spectrum of ' purified ' natural waters (see SVERDRUP *et al.*, 1942, Chap. 3; HUTCHINSON, 1958, Chap. 6). Although these measurements have served to demonstrate a general similarity of transmission spectra, considerable discrepancy exists between individual sets of measurements in the blue violet region of the spectrum. Because of techniques involved and the extensive nature of the studies, the investigations by JAMES and BIRGE (1938) must be considered to be the most representative of light absorption by pure water. Their measurements do not differ greatly from the previous ones made in the red region of the spectrum, but the transmission maximum extends

farther into the blue than previously reported, (Fig. 1). CLARKE and JAMES (1939) obtained a similar spectrum for 'fine' filtered coastal water which was significantly less transparent in the blue region. According to JERLOV, the clearest sea water

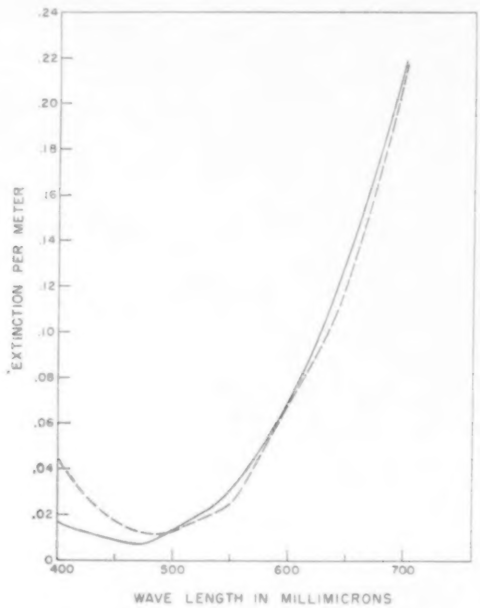

FIG. 1. Comparative extinction of pure water (JAMES and BIRGE 1937) solid line, and filtered sea water (CLARKE and JAMES 1939) dotted line.

Table 1. Wavelength of maximum transmission and the percentage of light of this colour transmitted in five different types of ocean, from (JERLOV 1951a)

Types of ocean water	*Wavelength of maximum transmission*	*Percent transmission per metre*
Clearest oceans	470	98·1
Average oceans	475	89·0
Clearest coastal	500	88·6
Average coastal	550	72·4
Average inshore	600	60·8

does not differ markedly from JAMES and BIRDGE's pure water. He prepared transmission curves for ocean waters of different transparency, using his own observations, data of POOLE and ATKINS (1937) and of UTTERBACH (1936). Table 1 shows the wavelength of maximum transparency in different types of coastal and ocean water designated by JERLOV. The clearest ocean water has a transmission maximum at

470 millimicrons, while in less transparent ocean water the maximum lies between 475 and 500 millimicrons. In turbid coastal waters, maximum transmission is between 550 and 600 millimicrons. This ' shift ' in the wavelength of maximum transmission, equivalent to changes in colour of different types of ocean water, has been attributed to the combined effects of selective scattering and absorption by dissolved yellow substance (KALLE, 1938, 1939).

The following discussion demonstrates that the absorption of light by living phytoplankton can selectively influence the absorption of submarine light, and spectral shifts, comparable to those in Table 1, can be produced by increasing the concentrations of phytoplankton.

ABSORPTION SPECTRA OF LIVING PHYTOPLANKTON

The combined absorbencies of natural populations of phytoplankton could be expected to vary from population to population; however, there is no evidence of great variations in the pigment composition of groups normally found in abundance in natural marine populations. For example, spectral curves for cultures of dino-

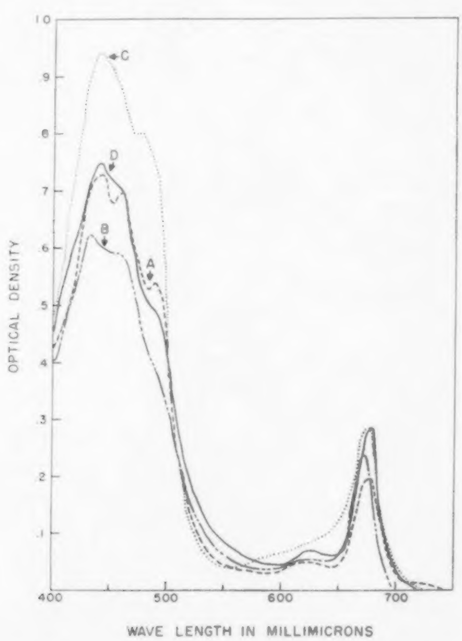

FIG. 2. Pigment spectra of living phytoplankton, *A.* Diatom *Cyclotella sp.*, *B.* Dinoflagellate, *Amphidium sp.*, *C.* green Flagellate *Chlamydomonas*, *D.* Natural population sampled from Woods Hole waters.

flagellates, diatoms, green flagellates and a natural population sampled from Woods Hole waters (Fig. 2) all show an absorption minimum in the green, strong combined chlorophyll and carotenoid absorption in the blue, and the red absorption by chlorophyll *a*. These spectra were determined by the cleared millipore filter method (YENTSCH, 1957), and hence represent principally the absorption of the pigment

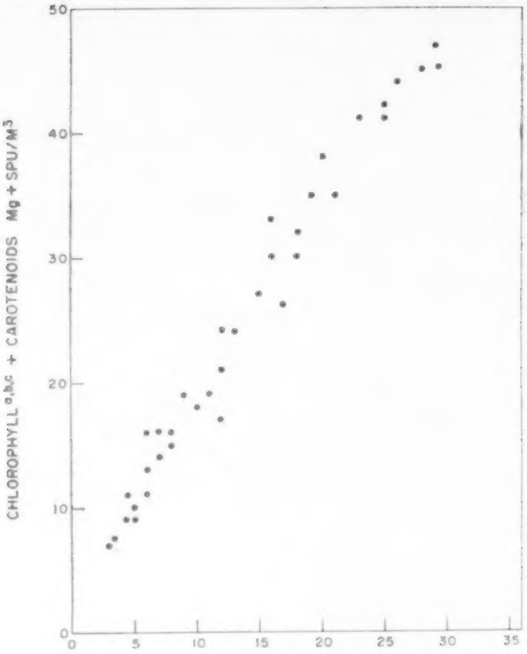

FIG. 3. Relationship between Chlorophyll *a* and total fat soluble pigments in natural populations of phytoplankton sampled from coastal waters and inshore waters.

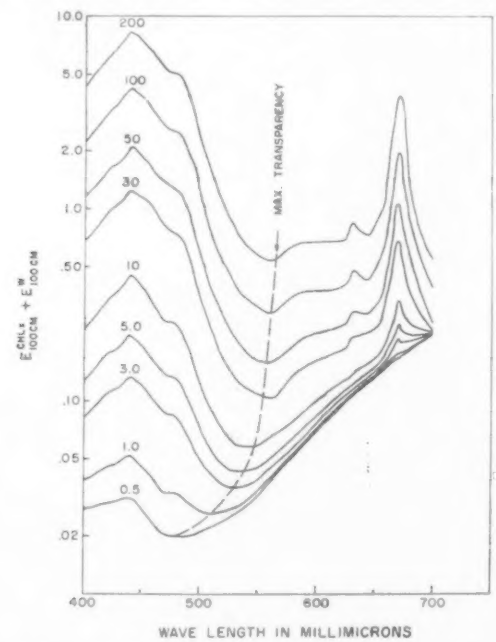

FIG. 4. Combined absorption coefficients for pure water and plant pigments. Numbers adjacent the curves indicate the chlorophyll concentration in mgs./m³.

within the plant.* Particularly important in this discussion is the intense pigment absorption in the blue region (400–500 mμ) where pure water has a minimum absorption (Fig. 1). Thus, the maximum transmission by pure water coincides with the maximum absorption of algal pigments, whereas the red chlorophyll absorption band falls in the range of high absorption by water.

THE EFFECTS OF DIFFERENT QUANTITIES OF PHYTOPLANKTON PIGMENTS ON THE ABSORPTION SPECTRA OF PURE WATER

The total effects of absorption by phytoplankton pigments and by pure water is estimated by summing their respective absorption coefficients. The assumption is made that the quantity of chlorophyll can be used as an index of total plant pigment. Data shown in Fig. 3 supports this assumption throughout a wide range of pigment values in natural populations. Optical density (E) was measured at every ten millimicrons throughout visible wavelengths in a Beckman DU spectrophotometer. Using the filter method chlorophyll concentrations are expressed in terms of a 10 cm light path, thus for given wavelengths an extinction coefficient $E^{1\,\mathrm{mg\,Chl}}_{100\,\mathrm{cm}}$ can be obtained (Table 2). The absorption by different concentrations of chloro-

Table 2. Specific absorption coefficients (E) *for Chlorophyll and pure water*

Wavelength in millimicrons	$E^{1\,\mathrm{mg\,Chl}}_{100\,\mathrm{cm}}$	$E^{\mathrm{w}}_{100\,\mathrm{cm}}$ *
400	0·0220	0·0160
410	0·0260	0·0150
420	0·0320	0·0130
430	0·0350	0·0110
440	0·0420	0·0100
450	0·0380	0·0090
460	0·0320	0·0080
470	0·0260	0·0070
480	0·0250	0·0080
490	0·0190	0·0100
500	0·0110	0·0150
510	0·0075	0·0180
520	0·0050	0·0210
540	0·0031	0·0260
560	0·0025	0·0360
580	0·0030	0·0500
600	0·0030	0·0700
625	0·0030	0·0950
630	0·0038	0·1000
645	0·0030	0·1230
650	0·0035	0·1300
655	0·0040	0·1360
660	0·0060	0·1440
665	0·0100	0·1520
670	0·0180	0·1590
675	0·0107	0·1670
700	0·0018	0·2150

* JAMES and BIRGE (1938)

phyll may be obtained by multiplying these values by appropriate concentrations. The combined absorption of phytoplankton pigments and of water is computed by summing the specific absorbence by chlorophyll, $E^{\mathrm{Chl}x}_{100\,\mathrm{cm}}$ at x concentration and

*Spectral analysis of *in vivo* pigment systems of plant cells has been extensively used in connection with other physiological studies.

the specific absorption values of pure water, $E^{w}_{100\,cm}$ (JAMES and BIRGE, 1938). Visible spectra representative of combined absorbencies are shown in Fig. 4. The intense blue absorption by phytoplankton pigments increases the total absorption in this region. Increases in chlorophyll concentration changes the wavelength of minimum absorption from blue toward green, a shift analogous to the shift observed in ocean waters of decreasing transparency. Because of the intense absorption by water in the red region, the chlorophyll peak at 675 millimicrons imparts almost no selective absorption when pigment concentrations are low. Therefore, in the open oceans where chlorophyll concentrations are generally below 1·0 mg/m^3 the absorption by the red band of chlorophyll is small, relative to that of water.

The absorption of blue light by phytoplankton is similar to the absorption by KALLE's 'yellow substance,' hence the combined effects of these would produce a residual absorbency in this region. Further evaluation of the relative importance of phytoplankton and of yellow substance must await the comparison of submarine spectral curves in water masses containing different concentrations of phytoplankton pigments.

DISCUSSION

JOSEPH (1949), TYLER (1958) and BURT (1958) have emphasized the importance of using narrow band filters when making light measurements underwater. When measurements are made in conventional spectrophotometers such as BURT's 1955a, 1955b, 1958 observations, the dominance of parallel light passing through suspensions of particles can lead at times to poor results. Measurements of optical density in dilute suspensions of phytoplankton generally yield spectral curves with little or no absorptive definition (Fig. 5). This is because the light transmitted to the phototube after passing through the sample cell is composed of both parallel and scattered light. In most spectrophotometers the geometric relationship between the sample and the phototube allows a considerable fraction of the scattered light to go undetected, so that the detected light is largely parallel light whose attenuation is independent of wavelength, since ratio measurements are made. SHIBATA (1958) has referred to this type of measurement as quasi-attenuance and gives the characteristics of the E units as p^1 *Epdf* where the p^1 to the left of E is the parallel light of the reference beam, whereas symbols to the right refer to the type of light passing through the sample, that is, parallel and diffuse (scattered). The magnitude of the diffuse light reaching the photocell is a function of the amount of scattering and the geometry of the spectrophotometer.

SHIBATA (1957, 1958) has obtained sharp absorption bands by placing opal glass between sample and photocell. In this manner, light reaching the photodetector is completely diffuse. Identical fractions, or nearly so, of diffuse and parallel light strike the phototube after passing through opal glass. The optical density measured in three ways on a suspension of *Skeletonema* culture are given in Fig. 5. Curve A is the direct measurement on the cell suspension; Curve B was obtained by using SHIBATA's opal glass techniques; Curve C was obtained by the cleared millipore filter method. Sharp absorption bands were obtained by using the opal glass or the cleared millipore filter method. In the latter method the portions of diffused and parallel light are kept nearly constant by concentrating the absorptive materials on a millipore filter, scattering is reduced by narrowing the light path, and the filter is

rendered transparent by applying cedar oil. Spectral curves obtained by either of these two improved methods show much sharper absorption peaks than conventional measurements on dilute suspensions.

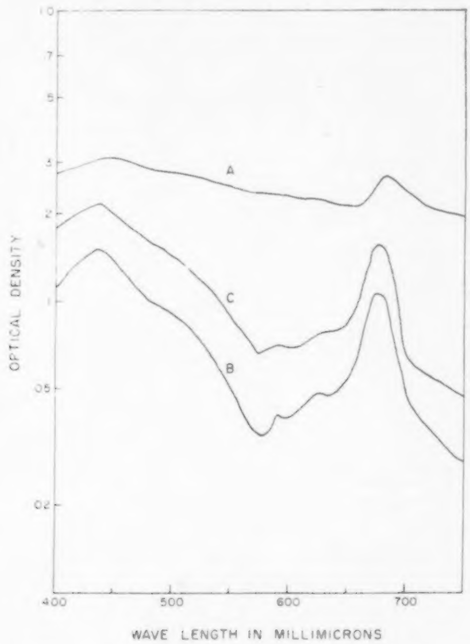

FIG. 5. Attenuation spectra of sea water suspension of *Phaeodactylum tricornutum* by different techniques, Curve *A*, conventional spectrophotometry, Curve *B*, opal glass technique, Curve *C*, cleared millipore filter technique.

Fig. 6 further illustrates the inadequacies of determining spectral curves of natural waters using conventional spectrophotometric techniques. Water samples were collected from a small estuary off Great South Bay, Long Island, New York (see RYTHER *et al.*, 1958). The colour of the estuary at this time was yellow-brown, and chlorophyll measurements revealed concentrations in excess of 100 mg/m^3. Microscopic examination by Dr. E. M. HULBURT revealed that the dominant phytoplankton was the dinoflagellate *Prorocentrum minimum*. Optical density measurements were made immediately on the raw water sample. A Beckman DU spectrophotometer was used with a 10 cm light path. For a reference, AA millipore filtered water from the estuary was used. Comparison with distilled water revealed no selective attenuation in the reference. Curve *A*, Fig. 6, shows the quasi-attenuance by the suspension, Curve *B* the attenuance of the suspension on a ' cleared ' millipore filter, and Curve *C* an acetone extract of the filtrate. The much greater absorptive definition gained by the cleared filter, as compared to optical density measurements made directly on the suspension, is quite apparent. Even when chlorophyll concentrations are larger, as was the case later during the same day of sampling, the absorptive ' bumps ' observed in the measurement of the suspension are by no means as clearly defined as are the measurements by the ' cleared ' filter technique.

Spectral measurements on natural waters containing suspended particles such as phytoplankton can probably be greatly improved by using SHIBATA's opal glass or the cleared filter technique. In clearest ocean waters, however, the light path must be sufficiently long to gain necessary sensitivity. Submarine spectrophotometers

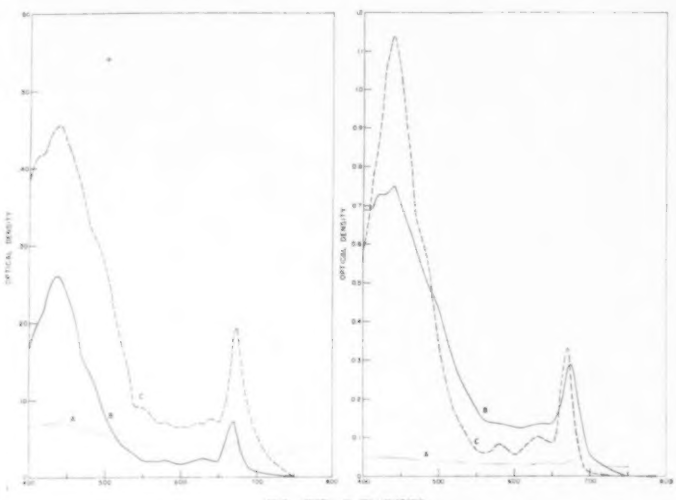

FIG. 6. Visible spectrum of water sampled from Senix Creek estuary, June 15th, 1958, by different techniques. Curve *A*, conventional spectrophotometry, Curve B, cleared millipore filter, Curve *C*, Acetone extract.

may obviate the technical difficulties of long light paths. However, one may still question whether or not quasi-attenuance is obscuring true extinction. Submarine measurements conducted well below the sea surface probably are representative of true extinction because of the diffuse light at these depths resulting from multiple scattering.

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On the problem of the antiquity of the deep-sea fauna

L. A. ZENKEVITCH and J. A. BIRSTEIN

(*Received November* 24 1959)

Abstract—The colonization of the abyssal zone by animals has extended over a very long geological time. The recent deep-sea fauna contains species which immigrated into the abyssal zone at different periods.

It is impossible to agree with BRUUN that owing to a sharp decrease of the temperature of bottom waters during the late Tertiary the ancient deep-water fauna died out and that the abyssal zone was repopulated by young Quaternary forms. Since the determinations of paleotemperatures on which this concept is based were obtained by using shallow-water rather than deep-water Foraminifera such a conclusion seems questionable. It is further contradicted by the existence in the abyssal zone of many undoubtedly ancient elements (2 species of *Neopilina, Spirula, Pogonophora* etc.) and by the absence of a true deep-water fauna in deep basins, which were formed during the Quaternary (Japan, Mediterranean and Red seas).

The computations of MENZIES and IMBRIE, which led these authors to the concept of a relatively young deep-water fauna are likewise far from convincing. The groups selected for analysis are not characteristic of the deep-sea fauna; they include only about 11 per cent of the species recorded from depths exceeding 3000 m. The dominant groups of the deep-water fauna, rich both in number of species and in biomass, are not preserved in fossil condition and were not taken into account by MENZIES and IMBRIE.

An analysis of the systematic position and pattern of vertical distribution of many important groups of deep sea animals permits us to distinguish among them ancient and young settlers of great depths. Approximate counts show that the percentage of primitive archaic forms in the abyssal fauna is far higher than in the fauna of the shelf, thus providing evidence of the greater antiquity of the abyssal fauna.

INTRODUCTION

RECENT intensive studies of great oceanic depths carried out by the expeditions of the *Galathea, Vitjaz, Vema* and others, have revived certain long-standing and controversial questions. One such problem concerns the age of the deep-sea fauna. In the early days FORBES (1859) and HUXLEY (1896) and more recently SVEN EKMAN (1953) together with other scientists, have emphasized the presence of numerous ancient archaic forms among the deep-sea fauna. We agree with these authors on the basis both of data in the literature and from a preliminary analysis of the material collected by the *Vitjaz* in the north-western part of the Pacific Ocean (ZENKEVITCH and BIRSTEIN, 1956).

On the other hand MURRAY, as early as 1895, pointed out the inconsistency of the concept of the antiquity of the deep-sea fauna, since it contains fewer archaic forms than the fauna on the continental shelf. Recently BRUUN (1956) and MENZIES and IMBRIE (1959) have expressed their decided opinion about the relative geological youth of the deep-sea fauna, supporting their viewpoint by very interesting considerations and statistics.

GENERAL STATEMENTS

In discussing this complicated problem we must first of all take into account the disparity of age between the different elements which compose the deep-water fauna today. Its formation seems to have been a long-term process of gradual and prolonged migration of shallow-water derivatives into the great depths. It may be assumed that this process is as old as the oceanic fauna itself, going far back into the Proterozoic.

A tendency to widen their range of distribution is inherent in all organisms. As regards marine animals their main chance of extending their habitat was, and still remains, the conquest of great oceanic depths.

DAVITASHVILI (1943), on the basis of paleonotological data, writes: '... the initial forms of all types had to live on the bottom of the euphotic stretch of shallow waters ...' (p. 21), and, further, '... in the most ancient periods of the history of the organic world all the more or less deep and relatively unfavourable parts of the sea were devoid of animal life, or were very scantily populated. Later the population of these parts gradually increased' (p. 22).

ANDRIASHEV (1953) carried out an analysis of deep-sea fishes which permitted him to differentiate two groups that settled in great depths at different times, namely a group of primary-deep, and a group of secondary-deep species, the latter comprising younger immigrants*.

Such a differentiation has also been found to apply to the Decapoda (BIRSTEIN and VINOGRADOV, 1953) and Mysidacea (BIRSTEIN and TCHINDONOVA, 1958). BEURLEN (1929) points out the consecutive penetration of decapods into the deeps during the late Jurassic, the late Cretaceous and the Eocene, and associates their migrations with the powerful oceanic regressions of these epochs.

The remarkable Monoplacophoran mollusc, *Neopilina galatheae*, a relative of the shallow-water species of the Lower Palaeozoic (LEMCHE 1957), is generally considered as one of the most ancient inhabitants of great depths. As will be seen, this mollusc, in respect to the antiquity of its origin, is no exception: it is but one instance among the majority of deep-water animals. However the deep-sea fauna comprises not only such ancient species but also some very young immigrants from shallow waters.

One of the immediate objectives of the study of deep-water faunas is the determination of the ratio of relatively ancient and relatively young species. Age disparities are observed alike in faunas from shallow-water marine, oceanic, fresh-water and terrestrial environments, but the degree of predominance of species and genera of different geological ages will vary depending on the environmental conditions which may have favoured the conservation of archaic forms, or, conversely, fostered the formation of new progressive groups.

The solution of this problem is greatly impeded by the lack of reliable methods of investigation. As will be shown below, palaeontological evidence is not convincing since no data are available on the deep-water fauna of ancient times. Nevertheless some legitimate distinctions may be drawn from a taxonomic analysis of animal groups at present dominant in great oceanic depths. Thus, certain groups are richly

*It will be probably more correct not to draw too sharp a line between these two groups, but to consider them as more ancient and more recent components of the deep-sea fauna.

represented by species and genera in the deeps and have but few, if any, representatives in shallow waters. The great diversity of representatives of these groups in deep waters may be interpreted in two ways : they are either remnants of a fauna dominant in shallow-waters in ancient times, or they have had enough time during their stay in abyssal depths to evolve numerous species and genera. No other alternative seems possible. In both cases these groups must be of very ancient origin since their dying out in shallow waters and descent into great depths, as well as the advanced process of speciation, must have extended over a very long period. In our opinion no formation of major taxonomic units occurred under abyssal conditions : there was simply an adaptive radiation into species and genera (ZENKEVITCH, 1958). It appears therefore that those higher taxonomic units, mainly, or entirely confined to great oceanic depths, should be most correctly regarded as relicts which in former times lived under the favourable conditions of the shallow seas and were displaced by relatively young and more progressive groups. Whether their descent into great depths and disappearance from shallow waters occurred during the Palaeozoic, Mesozoic or Cenozoic, is a matter of secondary importance. We can, however, be sure that the great oceanic depths play the part of refuges for relatively primitive relict groups which in their struggle for existence had to desert the more favourable conditions of life in the shallow waters.

As examples of such relict and undoubtedly very ancient groups, along with the Monoplacophora, may be named *Pogonophora*, the starfishes Porcellanasteridae and the bivalves of the genus *Spirula*.

The class (type ?) *Pogonophora*, related to the Enteropneusta and Graptolites contains 2 sub-orders, 7 families, 9 genera and some 70 species (IVANOV, 1957). Only two of the genera (*Siboglinum*, *Oligobrachia*) occur both in deep and in shallow waters; all others are confined to great depths. All the stenobathic shallow-water types of *Pogonophora* belong to the highly specialized genus *Siboglinum*, and presumably are forms that have returned to shallower depths.

The starfish family Porcellanasteridae is generally regarded as one of the most primitive families of the order Phanerozonia, whose fossil representatives are known beginning in the Middle Cambrian. Of the 47 species of this family only one, and at that the most specialized of them, was found in a depth of 925 m; all the others inhabit greater depths, and 37 of them (i.e., 70 per cent) do not ascend above 2000 m.

Many other examples can be cited confirming the existence of numerous families and taxons of higher rank, which have been preserved in great oceanic depths, due to a certain process of evolution (Isopoda : Monostylidae, Haploniscidae, Janirellidae, and others). Their transmigrations, withdrawal from shallow depths and evolution must have required a relatively long time and their colonization of the great depths must have occurred in the very remote past.

That the process of formation of the deep-sea fauna must have been a very long one is shown by many other facts. It is well known that the great depths of the Japan Sea, which are of recent origin, have no truly deep-sea fauna; first, the Pacific deep fauna was prevented from penetrating by the shallow straits which connect the ocean with the Japan Sea, and secondly, there has not been time enough for the formation of an endemic abyssal fauna.

The same applies to the Polar basin, the Mediterranean Sea and the Red Sea. Their deeps are of too recent an origin to have acquired a deep-sea fauna of their own.

What has been written above is in concordance with the statement of Ekman (1953), that: '. . . in any case, it can be regarded as established that a deep-sea fauna has existed for a very long time' (p. 310).

Let us now consider what arguments are presented in support of the contrary viewpoint.

PALAEOTEMPERATURES AND ORIGIN OF DEEP-SEA FAUNAS

Bruun (1956), reasoning from the data of Emiliani and Edwards (1953) on the ratios of oxygen isotopes in foraminiferal shells from the bottom cores collected by the Swedish expedition *Albatross*, concludes that the temperature of bottom waters decreased by 8° during the latter half of the Tertiary. Bruun argues that such a temperature change must have killed many members of the abyssal and hadal faunas. As he remarks : Only the relatively eurythermic and eurybathic species could survive. It was only during the Quaternary that the great depths were colonized again.

Determinations of bottom water temperatures were made by Emiliani (1954) for the Oligocene from *Cassidulina spinifera* Cushman and Jarvis, and for the Miocene from *Gyroidina zelandica* Finlay and *Laticarinina bullbrocki* Cushman and Todd. All the three species of Foraminifera used for the determination of paleotemperatures are diagnostic fossils for shallow water deposits of their respective ages. It is very doubtful that they lived in abyssal depths contemporaneously. According to Cushman and Stainforth (1945), *C. spinifera* and *L. bullbrocki* inhabited depths ranging from 50 to 200 m.

Most probably there was a secondary shifting of empty shells of these Foraminifera to a greater depth, such as was proved by Emiliani and Epstein (1933) to have occurred for *Elphidium*. If so, the temperature determined for these species refers not to the abyssal but to the bathyal and sublittoral zones. This explains the higher values of water-temperature compared with those of the abyssal waters of today and makes agreement with the far-reaching inferences made by Bruun from the data of Emiliani impossible (Birstein, 1959).

Another fact disproving the probability of sharp temperature changes in abyssal waters, is the undoubtedly long existence in these waters of several species whose antiquity is not questioned by Bruun. This author quite rightly characterizes *Neopilina galathea* as a ' living fossil,' pointing out its affinity with species of the Lower Palaeozoic. According to Yonge, (1957), *Neopilina* migrated into abyssal depths in the distant past. There is no reason whatever to ascribe to this interesting mollusc a high degree of eurythermy and a resistance to very abrupt changes of temperatures, changes, which Bruun believes were fatal to other ancient abyssal animals.

Morover, it may be seen from the evidence cited, that the history of the formation of such deep-water forms as *Pogonophora* or Porcellanasteridae does not fit into the narrow limits of the Quaternary; the span of time between Early Quaternary and today is too short to allow for the formation of a true deep-sea fauna. This is shown by the evidence from the Japan, Mediterranean and Red Seas, whose great depths failed to develop a deep-sea fauna of their own during the Quaternary.

PALAEONTOLOGICAL CRITERIA OF THE AGE OF DEEP-SEA FAUNAS

Menzies and Imbrie (1958) made an interesting attempt to determine without bias the geological age of the bottom fauna living in different depths. With this object in view they calculated the ratios of genera and families of different geological ages for six groups of bottom-animals from different depths. It was found that in five of the selected groups the relative age of genera decreases with depth, so that the abyssal fauna contains fewer archaic genera than the shallow-water fauna and consequently is to be regarded as a younger one.

These data, obtained for the Porifera, Scleractinia Cyclostomata, Cheilostomata and Brachiopoda, were not substantiated by the Foraminifera. The six groups used for the computations were selected as being most representative, since ample palaeontological material was available for each of them as well as detailed data on their present vertical distribution.

The groups selected by Menzies and Imbrie are indeed richly represented as fossils, but none of them, with the sole exception of the Foraminifera, is characteristic of the deep fauna of today.

The Scleractinia are well represented and flourish in shallow-depths, but below 3000 m they are represented by 4 genera and 4 species only. They were rare in the collections of the *Vitjaz* from depths greater than 3000 m.

According to Silén (1953) only 46 of the 3850 species of Bryozoa occur in depths exceeding 3000 m and only 18 of them are confined to these depths alone. Osburn (1944) reports 522 species of Bryozoa from the Pacific Coast of America. Only 3 of them are known to be from depths greater than 1000 m. In the rich deep-sea collections of the *Vitjaz* taken below 2000 m, only 600 samples contained bryozoans (2 species of the genus *Kinotoscias*).

According to Dall (1921) (taking due account of all subsequent nomenclaturial corrections) 9 species of Brachiopoda are known from depths greater than 2000 m, 3 species from depths greater than 3000 m and only one species descends below 4000 m. No brachiopods whatever were encountered in the deep-sea collections of the *Vitjaz*.

Vinogradova has meticulously recorded the number of species in different groups of animals occurring in depths greater than 200 and 300 m (see Table 1). The Polychaeta are found to rank first in specific diversity; they are followed by Holothurioidea and Asteroidea, then come Spongia, Bivalvia and Gastropoda, whereas the groups worked up by Menzies and Imbrie, i.e. the Brachiopoda, Bryozoa and Scleractiniae (the latter forming but an insignificant part of the abyssal Colenterata) lag far behind most other groups of bottom animals. Only 11 per cent of all species encountered below 3000 m are included in the groups selected by Menzies and Imbrie. The extension of these conclusions to the whole abyssal fauna is unlikely to be correct when they are based on so small a fraction.

Data bearing on the quantitative development of the different groups offers further support to our notion of the antiquity of the deep water fauna.

In the Kurile-Kamchatka Trench no Brachiopoda or Bryozoa were encountered, and Scleractinia occurred infrequently and in single specimens. The Spongia account for more than 70 per cent of the whole biomass of benthos in depths of about 1000 m, but they disappear gradually between 2000 and 3000 m. Below 2000 m Holothuroidea,

Asteroidea, Polychaeta etc. become dominant (ZENKEVITCH and BIRSTEIN, 1956). An analogous sharp decrease of sponges with depth down to 2000 m was observed in the Antarctic (BELJAEV and USHAKOV, 1957).

Table 1. *Number of species of bottom invertebrates in different depths*

Groups	*Total*	*Depth*	
		2000 m	3000 m
Spongia	5000	163	112
Coelenterata	9000	141	97
of them :			
Scleractinia			4
Polychaeta	4500	251	190
Echiuroidea	110		12
Sipunculoidea	304	31	21
Bryozoa	3850	66	48
Brachiopoda	160	23	13
Cirripedia	700	71	39
Tanaidacea	250		25
Isopoda	2000		62
Amphipoda	6500		21
Decapoda	8321	76 + 3	38
Pantopoda	400	58	35
Gastropoda	90,000	240	101
Bivalvia	15,000	191 ?	105
other Mollusca		47	24
Asteroidea	1500	232	151
Ophiuroidea	1900	185	108
Echinoidea	860	90	58
Holothuroidea	1100	206	154
Crinoidea	613	45	19
Pogonophora	73	57	47
Ascidia	1600		38
			1518

Consequently, in respect both to the number of species and to the degree of quantitative development the groups chosen by MENZIES and IMBRIE form too small a part of the deep-sea fauna to be regarded as truly representative. On the other hand, such groups as Holothuroidea, Asteroidea, Polychaeta, Mollusca, Isopoda, Echiuroidea etc., fully adapted to life in abyssal depths and constituting the bulk of the deep-sea fauna were not analyzed by MENZIES and IMBRIE because of the lack of palaeontological evidence. The groups for which good palaeontological material is available are not characteristic of the deep-sea fauna, whereas predominant groups especially adapted to great depths are almost unknown or entirely unknown in fossil condition or have not been adequately investigated.

The paucity of palaeontological material for dominant groups of the abyssal fauna may be explained by the well known phenomenon of increasing $CaCO_3$ solubility with depth.

The disappearance of animals with calcareous skeletons, the reduction of skeletons or the alteration of their composition in great depths have been well demonstrated by VINOGRADOV (1944). FAGE (1954) has written about the deep-sea animals as follows : '... Aussi constatet-on l'absence ou la réduction de leur squelette calcaire ' (p. 15). It is nonetheless the calcareous skeleton that is best preserved in fossil condition.

This dissolution of $CaCO_3$ is not however the only limiting factor in the determination of the age of modern deep-sea fauna on the basis of palaeonotological data. Another reason why no convincing results can be obtained by the method employed by MENZIES and IMBRIE is the well known fact that palaeontologists deal exclusively with shallow-water animals. Deep-water deposits very rarely outcrop on the continents and thus are almost inaccessible to research. " We know only that no deep-sea deposits are found on massifs and shelves, and in the geosynclines they occur but sporadically ' is a statement on this subject by BUBNOV (1930).

Therefore, when we determine the geological age of the genera and families which today live at a given depth we are certainly not determining their actual age, but are merely establishing to which shallow-water fauna of particular periods they are related. If a group of animals migrated into great depths during the Pre-Cambrian there is no chance whatever of discovering its representatives in a fossil condition. For this reason the great antiquity of the fauna cannot be determined by the method of MENZIES and IMBRIE. The earlier the migration the less likely that the affinity can be traced between a recent deep-water group and a shallow-water group of the past, and the less reliable the results obtained by the method of MENZIES and IMBRIE. The statement of these authors concerning the higher proportion of ancient elements in the fauna of the shelf as compared with the abyssal depths can be easily explained by the obvious fact that it is not the fauna of the abyssal waters but the fauna of the shelf that has been preserved in fossil condition.

From the foregoing discussion it follows that it would be possible to use the method of MENZIES and IMBRIE if : (1) inhabitants of all vertical zones of the ocean had been equally preserved in fossil condition and (2) if the major groups of the modern abyssal fauna could be in general preserved in fossil condition. As, however neither of these conditions is fulfilled we can hardly admit the possibility of determining the age of recent faunas of different vertical zones, and especially of the abyssal depths, by the method of MENZIES and IMBRIE.

ANCIENT ELEMENTS IN THE COMPOSITION OF THE DEEP-SEA FAUNA

EKMAN (1953, pp. 308-310) gives several examples of ancient groups being confined to great depths. Since then new data have been obtained which allows the extension of this list, but the systematic composition of the abyssal fauna is still insufficiently known and a great part of the vast material collected during recent cruises is not as as yet worked up. As it is thus impossible to achieve an analysis of the entire deep-sea fauna that would allow the discovery of its archaic representatives we are merely pointing out some groups to which the notion of geological youth is quite inapplicable.

Mollusca

Monoplacophora.

Neopilina galatheae and *N.* (*Vema*) *ewingi* – the only living representatives of this class known in fossil condition from the Lower Palaeozoic were found off the west coast of Mexico at a depth of 3590 m and off the west coast of Chile at a similar depth (CLARKE and MENZIES, 1959).

Bivalvia

'The bivalve fauna of the abyssal zone of the North-western Pacific has been found to consist of about 25 genera comprising more than 50 species . . . Among

the 18 genera, whose species inhabit depths of 4000–6000 m the most frequent and numerous are : *Spirula, Tindaria, Malletia, Neilonella, Neilo, Leda* (subgen. nov.), *Soldia, Soldiella* and *Nucula*. All these genera belong to the Taxodonta – the most primitive and ancient forms of Bivalvia.' (Filatova, 1958).

The abyssal family Malletidae is generally considered as the most primitive family of the Taxodonta. According to Filatova (1958a) its representatives are dominant in abyssal depths over other groups of bivalvia not only in the North-western Pacific but also in other parts of the ocean. The genus *Spirula* of the Malletidae comprises 5 recent species and (according to F. Prantl) is closely related to the Silurian genera *Silura* and *Hercynella*, being in this respect an analogue of *Neopilina*.

Crustacea

Harpacticoida. V. Brodzky informed us that she has found 16 species of Harpacticoids in the North-western Pacific at depths exceeding 4000 m.; half of them belong to the most primitive families of the sub-order Cerviniidae, and Canuellidae.

Mysidacea. Tattersall (1951) summarizing palaeontological data for this order write: 'In all cases where details of the morphology are available the fossil forms show greater affinity with the Lophogastridae than with any other family, thus bearing out the view that this is the most primitive family of the order' (p. 66).

The family Lophogastridae of today is almost entirely confined to abyssal waters and only the young of some species ascend to a depth of 200 m. The most primitive genera of this family and of the whole order, *Gnathophausia* Will.–Suhm and *Parachalaraspis* Birst. et Tchind., are dwellers in abyssal depths.

Isopoda. According to Wolff (1956) 62 species of the order Isopoda are found in the World Ocean at depths exceeding 3000 m and 53 of them (86 per cent) belong to the suborder Asellota. Judging from the collections of the *Vitjaz*, such a predominance of Asellota over representatives of other suborders is also a characteristic feature of the Pacific deep-sea fauna.

The suborder Asellota is considered to be the most primitive of the 6 suborders of Isopoda. 'They have preserved some primary features' writes Hansen (1916, p. 3) about this suborder.

Tanaidacea. Wolff (1956a) showed that the family Neotanaidae is dominant in abyssal depths over the family Apseudidae in respect to number of species. He writes : 'There is hardly any doubt that Neotanaidae is an archaic group of Tanaidacea as for instance Eryonidae and Homolodromiidae in Decapoda... Neotanaidae are (with one single exception) purely abyssal... Bruun (1956) is probably right in maintaining that most of the living fossils of the deep-sea are bathyal. (*We think this questionable* L.Z. and J.A.B.). However, Neotanaidae is a striking example of a family which unites high age with an almost purely abyssal occurrence, even including one or two hadal representatives.' (p. 235).

Decapoda. 'Zu der bekannten Tatsache, dass sich in der heutigen Tiefseefauna besonders viele altertumliche Typen finden, die in früheren geologischen Perioden im Littoral gelebt haben, liefern auch Decapoden gute Beispiele.' Es seien genannt :

(1) Die Penaeidae, die heute in der Tiefsee besonders gut vertreten sind und fossil bereits in der Trias vorkommen, also eine sehr alte Gruppe darstellen.

(2) Die Gattung *Phoberus* (Homaridae), die in *Palaeophoberus* des Jura (Dogger) einen nahen Verwandten hat.

(3) *Thaumastocheles*, ebenfalls eine Homaridae, der seine Verwandten in *Oncopareia* hat, der in Kreide und Eozän häufig war.

(4) Due Polychelidae, zu den Eryonidae gehörig, die sich von der Trias bis zur unteren Kreide finden, dann aber später fossil nicht mehr erhalten sind und erst recent wieder auftreten.

(5) Unter den Galatheiden stehen *Galatheites, Palaeomunidopsis, Munitheites* aus dem Jura dem rezenten *Uroptychus* der Tiefsee nahe.

(6) Unter den Krabben sind die primitivsten, die Homolodromiidae, mit der Prosoponidae aus Jura und Kreide nahe verwandt, ja sie werden sogar von GLAESSNER (1933) direkt zu ihnen gerechnet. Auch die heute wenigstens grösstenteils in der Tiefsee vorkommenden Homolidae treten fossil bereits in der Kreide auf.

Die sind also gute Beispiele für altertümliche Formen unter den heutigen Tiefseebewohnern; immerhin treten sie gegenüber den übrigen Decapoden der Tiefsee mengenmässig wohl zurück.' (BALSS, 1955, p. 1295–1296).

Echinodermata

Asteroidea.

One of the most primitive families within the most primitive order of starfishes Phanerozonia, known as a fossil, is the family Porcellanasteridae. 41 species of the 47 known species of this family are recorded from depths greater than 2000 m and 37 of them are not encountered above 2000 m. The most primitive family of another order – that of the Forcipulata – is the essentially abyssal family Brisingiidae. Seven genera and 41 species of this family were found below 2000 m. (BELJAEV, personal communication).

Holothuroidea.

More than 50 per cent of the Holothurian species encountered below 3000 m and more than 75 per cent of species occurring below 4000 m belong to the order Elasipoda. This order is confined mainly to abyssal regions. According to MADSEN (1953) more than half of the genera and about two thirds of the species of Elasipoda live below 3000 m. Below 2000 m 4 families, 18 genera and 95 species were encountered, i.e. 60 per cent of all genera and 61·3 per cent of all species of this order. In many trenches especially in the Kurile-Kamchatka Trench, the biomass of the Elasipoda exceed all other bottom animals taken together; in the Kurile-Kamchatka Trench at a depth of 8–10,000 m. Elasipoda account for 75–90 per cent of the whole biomass of benthos (ZENKEVITCH and BIRSTEIN, 1956).

As early as in 1882, THEEL characterized the Elasipoda as an ancient and primitive group. He writes : 'It follows from the facts above mentioned that the Elasipoda have retained many peculiarities characteristic of the larvae of Apoda and Pedata, and consequently that they have in many respects persisted without any sensible change for very long periods of time, and that they do not bear any genetic relation to the present representatives of the Apoda and Pedata, but are derived from ancestral forms of extreme antiquity.' (p. 146).

A subsequent detailed morphological analysis of this leading group of the abyssal and ultra-abyssal fauna led Ekman (1926) to the following conclusion ' Die Auffassung von Östergren und Becher, nach der die Elasipoden eine in manchen Hinsichten altertümliche Gruppe bilden, scheint mir als die einzig annehmbare.' (S.532).

Pisces

In general the following groups may be regarded as ancient deep-water fishes: the class Holocephala, the orders Bathyclupeiformes, Ateleopiformes, Giganturiformes, Saccopharyngiformes, Macruriformes, Halosauriformes, Notacanthiformes, Icosteiformes; the suborders Stomiatoidei, Opisthoproctoidei, Nemichthyoidei, Ceratoidei and others; the families Alepocephalidae, Bathylagidae, Moridae; most families of the order Scopeliformes (Myctophidae, Alepisauridae, Cetomidae and others), Owstoniidae, Chaunacidae, probably the Brotulidae and others. Most of the orders and families listed above belong to the lower phylogenetic groups of Teleostei (from the Clupeiformes to the Anguilliformes and Gadiformes); this allows us to infer a relatively ancient migration into great depths and a long-termed process of evolution under conditions of abyssal and bathypelagic environment." (Andraishev, 1953, p. 59).

Even this rather incomplete list shows that many leading groups of abyssal waters can be quite legitimately considered as being of ancient origin and having preserved features of primitive organization.

YOUNG ELEMENTS IN THE COMPOSITION OF THE DEEP-SEA FAUNA

We have already mentioned that the process of colonization of the abyssal zone by the different elements of its fauna was not continuous. This is shown by the fact that along with the specific ancient deep-water forms listed above there exist many groups of relatively young deep-water animals closely related to shallow-water forms. Examples may be cited of whole classes as well as of separate genera and species of such recent settlers whose stay in the abyssal zone has not been long enough for a marked morphological differentiation from their shallow-water ancestors, and who have no primitive archaic features.

An analysis of the geographical distribution and the affinities of deep-water Sipunculoidea carried out by Murina (in press) has shown that among the 304 species of this class only 31 are found below 2000 m and only 10 of them do not ascend to lesser depths. All these species belong to the widely distributed and highly eurybathic genera *Golfingia*, *Phascolion* and *Phascolosoma*. There are no deep-sea genera nor subgenera in the class Sipunculoidea.

Murina concludes from her analysis that ' the absence of a systematic differentiation of the abyssal sipunculid fauna from that of shallow-waters indicates that the passage of individual species to life at great depths must have taken place in the relatively near past and consequently the abyssal fauna of Sipunculoida is a young one.'

Somewhat similar data were obtained for the Pantopoda by Fage (1953). Forty species (10 per cent of all those known) are recorded from depths greater than 2000 m; 25 of them ascend to shallower depths. All the genera to which they belong are characterized by being markedly eurybathic in habit.

Among the abyssal Decapoda, along with the ancient deep-water species listed above, young deep-sea dwellers are encountered. Eleven species of the genus *Sclerocrangon* live within the boundaries of the shelf, 2 species descend below 2000 and only one of them – *S. zenkevitchi Birst. et L. Win.* has never been found above 2995 m. This is the only truly abyssal species of the genus, known only from the Bering Sea and the adjacent part of the Kurile-Kamchatka Trench. It is related to *S. derjugini* Kob. from the Okhotsk Sea and to *S. ferox* G.O.Sars from the Polar basin.

Each of these species is confined to a single relatively deep basin because of the absence of pelagic larvae, thus preventing wider distribution. Their morphological affinity allows us to assume a recent origin from a common shallow-water ancestor (BIRSTEIN and VINOGRADOV, 1953).

Fishes that have recently adapted themselves to life in great oceanic depths have been precisely characterized by ANDRIASHEV (1953). 'The secondary deep-water forms belong to families common to the continental shelf, representatives of which have become adapted to life in deep-waters. The family Cottidae is characteristic in this respect. A great number of secondary deep-water forms are found in the family Zoarcidae . . . and Liparidae. In other families secondary deep-water forms are less numerous (Lumpenidae, Agonidae, Scorpaenidae, Gadidae, Soleidae, Bothidae, Bothidae, Gobiidae, Nototheniidae, Torpedinidae and many others). Most secondary deep-water forms belong to phylogenetically young groups of Teleostei (mainly Perciformes) whose developments extends no further back than the Early or Middle Tertiary.' (p. 60–61). What then is the difference between ancient deep-water and secondary deep-water animals, apart from their systematic positions and their relation to shallow depths ?

First of all it must be noted that both groups are equally well adapted to life in great oceanic depths. The maximum depth at which fish are known to occur is 7529 m. It was from this depth that a *Careproctus* (*Pseudoliparis*) *amblystomopsis* was taken by the *Vitjaz* in May 1957 in the Northern part of the Japanese Trench. This fish, also described from the adjacent Kurile-Kamchatka Trench and obtained from a depth of 7230 m is without doubt a secondary deep-water species (ANDRIASHEV, 1955). The mysid *Amblyops magna* Birst. et Tchind., captured in the same haul in the Kurile-Kamchatka Trench is also a secondary-deep-water form. This is the greatest depth from which mysids are recorded (BIRSTEIN and TCHINDONOVA, 1958).

However, despite their similar adaptation to great depths, the ancient and secondary deep-water forms differ in respect to their relation to depth. This is shown by the dissimilar patterns of their vertical distribution. In most secondary deep-water animals the number of species regularly and rapidly decreases with increasing depth, whereas in the ancient deep-sea animals the number of species tend to increase with depth and begin to diminish only with the passage to the lower abyssal and the ultra-abyssal waters. These different patterns of vertical distribution are well illustrated in the diagram drawn by MURINA (Fig. 1), showing the comparative changes in the number of species of the secondary deep-water Sipunculoidea and the ancient deep-water Pogonophora (in both cases the total number of species is taken as 100 per cent). Judging from the literature on Elasipoda (MADSEN, 1953; EKMAN, 1953) and on some fishes (GREY, 1956) the vertical distribution of these groups can be shown by the same diagram as that for Pogonophora.

In many cases, differences are observed not only in vertical distribution, but also in the horizontal distribution. According to ANDRIASHEV secondary deep-water species of fishes have very narrow ranges of distribution and are confined mainly to the continental slope and adjoining parts of the abyssal zone. On the other hand ancient deep-water fishes are characterized by very wide, sometimes panoceanic ranges,

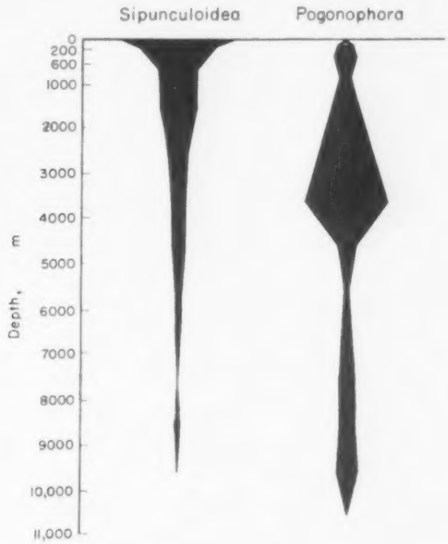

FIG. 1. Distribution of Sipunculoidea and Pogonophora according to depth and in relation to percentage of total species number.

extending over far-offshore regions of the World Ocean. This statement cannot be applied to all invertebrates without reservation. The ranges of many secondary deep-water invertebrates such as *Sclerocrangon zenkevitchi* and *Amblyops magna*, follow the same trends as those of the secondary deep-water fishes but there may still be exceptions to the general rule.

Thus we see that today certain criteria are available that permit us to distinguish relatively ancient and relatively young inhabitants of great marine depths without recourse to palaeontological criteria.

CONCLUSIONS

The essential problem posed in this paper, and one that cannot be conclusively answered at the present state of our knowledge is the determination of ratios of relatively ancient and relatively young elements in the faunas of the World Ocean, living at different depths. It is with this aim in view that we have discussed different criteria for the antiquity of certain animal groups.

If 1518 is taken as an estimate of the number of species of multicellular bottom invertebrates inhabiting depths in excess of 4000 m (Table 1) and 18,000 as the number of species in the shelf area, the approximate percentage of archaic groups (determined according to the criteria suggested in this paper) is 16 per cent in the abyssal zone and 0·00005 per cent in the shelf zone. These criteria cannot be

regarded as exact; they merely indicate the order of magnitude of the actual values. Nevertheless they allow us to state that ancient archaic elements are concentrated in great oceanic depths; these elements are immeasurably less important in the shelf area. If we were to agree with Menzies and Imbrie and take into account only those genera whose antiquity can be confirmed by palaeontological evidence, our conclusions are not affected. Although, according to these authors, the absolute number of ancient genera is somewhat lower in the abyssal than in the shelf area, the proportion of ancient genera to the few genera which compose the abyssal fauna is considerably higher than in the fauna of the shelf with its numerous genera. We would therefore conclude that the abyssal fauna is not younger, but far more ancient than the fauna of the shelf.

This conclusion is not unexpected. Owing to the uniform and stable environmental conditions and the sparse population of the abyssal zone, the evolution of its fauna must have been a much slower process than in the shelf area with its highly variable conditions, and dense population rich in species. There is no wonder that the abyssal zone has become a refuge where, as in caves, and presumably, interstitial waters, archaic forms are preserved almost unmodified.

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The total Iodine and Iodate-iodine content of sea-water*

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Abstract—Iodine in sea water samples from the Northeast Pacific and Arctic Oceans was determined by two independent methods of analysis, one of which was also capable of determining iodate. Both oceans showed a constant iodine-chlorinity ratio of $3{\cdot}3 \times 10^{-6}$ at depths from 250–4000 metres. Some significant variation was observed in the iodine chlorinity ratio in the surface layers. In the North Pacific from one- to two-thirds of the total iodine was present as iodate, with no discernible trends with depth or location. In the Arctic, the iodate increased with depth – from a minimum near the surface to a maximum at 500–1000 metres where 100 per cent of the iodine was found to be iodate. More iodate was present in the Arctic from 200–2000 metres than was present in any North Pacific sample.

Inland waters of the State of Washington showed iodine–chlorinity ratios about 15 per cent lower than oceanic stations, probably due to accumulation of iodine by benthonic algae.

(1) INTRODUCTION

IODINE in the oceans has been the subject of numerous investigations inspired by the biological and geochemical importance of the element. VINOGRADOV (1953) gave data on iodine in marine organisms, listing some data on iodine content of sea water. REITH (1930) gave an extensive review of the earlier determinations and presented his own findings on iodine content of sea-water samples from the Atlantic and Indian Oceans, and the Mediterranean and Red Seas. Since then, determinations of iodine in sea water have been made by CLOSS (1931), EVANS (1932), SKOPINTZEV and MICHAILOVSKAYA (1933), DUBRAVCIC (1955), and SUGAWARA and TERADA (1957). ZARINS and OZOLINS (1935) determined iodine in the low-salinity waters of the Baltic and Gulf of Finland. Nevertheless, knowledge of the distribution of iodine in the oceans is fragmentary. The factors which control its distribution are almost unknown.

The lack of suitable analytical methods and the fact that a large proportion of the samples analyzed were taken from coastal or surface waters may account for the large range of values reported for the iodine content of ocean waters. Thus, during the present century, values for iodine content of ocean waters as low as 13 γ/L were reported by VON FELLENBERG (1923) and 8 to 10 γ/L were obtained by SUGAWARA and TERADA, while REITH and EVANS found as much as 70 and 92 γ/L respectively. Of the above values, those of VON FELLENBERG and EVANS represent coastal waters; the values quoted from SUGAWARA and TERADA are for surface samples; REITH's value was from a Red Sea sample taken at 900 metres depth. Since atypical oceanographic conditions prevail at each of the sampling locations, it is difficult to distinguish real variations from what may possibly be the results of faulty analytical methods. Much the same thing can be said of the great majority of investigations of iodine in ocean water, since less than a dozen samples had been taken from the open ocean at

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depths greater than 100 metres before SUGAWARA and TERADA performed their work in the Pacific. Only WINKLER (1916) and CAMERON (1922) had reported on the forms of iodine present in sea water prior to 1957. Both of the latter found more than 80 per cent of the iodine present as iodate. SUGAWARA and TERADA found that the iodide content of their samples varied widely, while the total iodine content showed much smaller variations. They computed the difference between the iodide and the total iodine as iodate.

Fig. 1. Oceanographic Station Locations.

SHAW and COOPER (1957) discussed the results obtained by SUGAWARA and TERADA; they noted that iodate should be the thermodynamically stable form of iodine in the oceans, but that the iodate reported by SUGAWARA and TERADA should be considered to be hypoiodite because of the kinetics of the oxidation reaction by which iodate would be formed, and because the presence of hypoiodite would account for the iodine reported in the atmosphere. In reply, SUGAWARA and TERADA (1958) were joined by JOHANNESSON (1958) in denying that any detectable amounts of hypoiodite are present in sea water. SHAW and COOPER (1958) subsequently summarized the various points of view and concluded that iodate does indeed appear to be the form of oxidized iodine present in sea water, but that the first results obtained by SUGAWARA and TERADA could not be accounted for by the available information on mixing rates in the ocean and also did not explain the presence of iodine in the atmosphere.

DUBRAVCIC made use of a catalytic method to perform the first direct determination of iodine in sea water. He found 61 γ/L of iodine in a surface sample from the Adriatic. The lack of a sensitive direct method made it necessary for all other investigators to concentrate the iodine in their samples by precipitation, extraction, or distillation

before the samples could be estimated colorimetrically or volumetrically. The analyses were therefore time-consuming and prone to contamination or loss of iodine.

The authors (Barkley and Thompson, 1960) recently reported on two methods which were developed for the direct determination of iodine in sea water. One of these methods is similar to that used by Dubravcic; it makes use of the catalytic effect of iodine on the reaction between ceric sulphate and arsenious acid. The

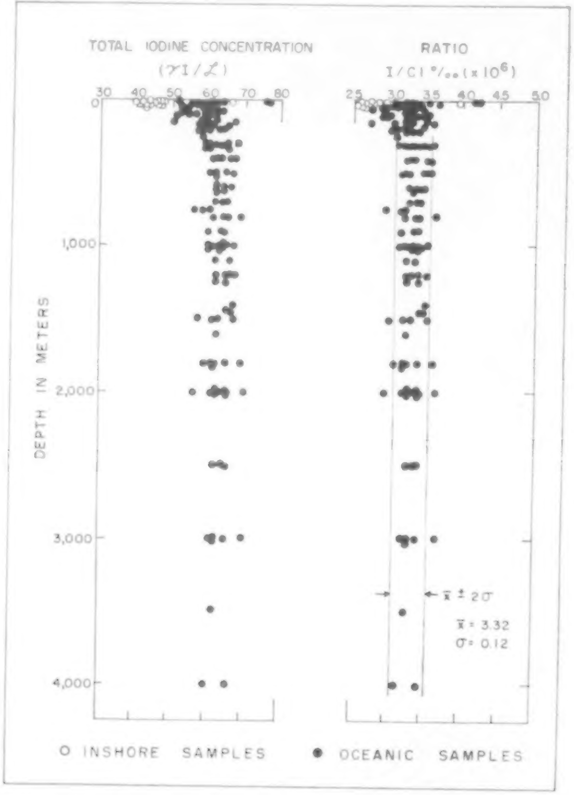

Fig. 2. Relationships between Iodine, Chlorinity and Depth.

catalytic method determines the total inorganic iodine in 25 ml of sea water with a precision of 1·3 γ/L for one standard deviation. The second method depends upon the reaction of any oxidized forms of iodine in the sample with excess iodide in acid solution to produce elemental iodine which can then be titrated amperometrically. By using two 100 ml samples, the oxidized iodine in one sample can be determined and reported as iodate, while the iodine in the second sample can be oxidized with bromine to the iodate form to determine the total inorganic iodine content. The amperometric method has a precision of 2·1 γ/L for one standard deviation.

Table 1 shows the results of the analyses of a number of oceanic and inshore samples for total iodine and iodate–iodine. The locations of the stations appear in Fig. 1. Fig. 2 shows the vertical distribution of total iodine and the iodine–chlorinity ratio for all samples. Fig. 3 shows the vertical distribution of iodate–iodine for

all samples for which the determination was performed. The envelope which encloses the total iodine values at depths greater than 200 metres of all oceanic stations is also shown in Fig. 3.

Samples from station 8 were subjected to duplicate analysis by both the catalytic and the amperometric methods for total iodine as a check on accuracy. The results show excellent agreement between the two methods.

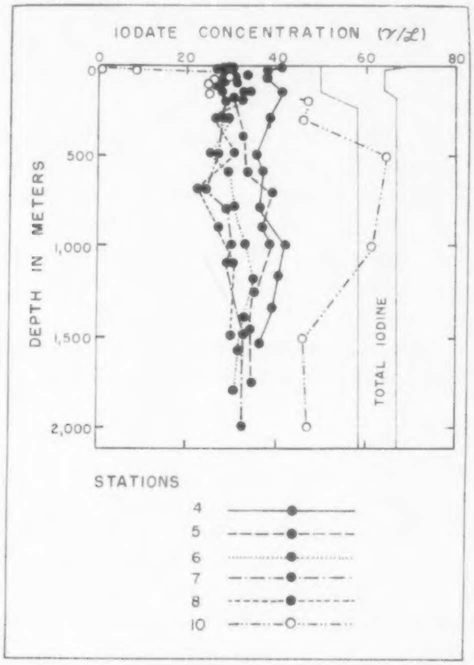

Fig. 3. Vertical Distribution of Iodate–Iodine.

(2) RESULTS

The data for total iodine may be summarized as follows :

(1) Below 200 metres depth the iodine–chlorinity ratio in the Arctic and the North Pacific was found to be constant and was $3{\cdot}32 \times 10^{-6} \pm 0{\cdot}12 \times 10^{-6}$ (one standard deviation).

(2) Above 200 metres the iodine–chlorinity ratio varies noticeably from the mean for deeper samples. There is some evidence of concentration of iodine at the surface and slight depletion, relative to chlorinity, below the surface down to 200 metres.

(3) The iodate–iodine data for the North Pacific did not show any definite trends with depth or location, although station 4, nearest the coast, seemed to contain slightly higher concentrations of iodate than did the other samples. The Arctic station, No. 10, was strikingly different from the North Pacific stations. No iodate was found in the shallowest sample and only a small amount was present at 25 metres. Concentrations of iodate comparable to those found in the North Pacific occurred between 50 and 150 metres, while larger amounts were found below these depths. At 500 and 1000 metres, all of the iodine was present as iodate.

(4) Inshore samples from the State of Washington show an iodine–chlorinity ratio some 15 per cent lower than offshore samples. One sample, however, taken approximately 1 metre from a mud bottom at 20 metres depth, had an exceptionally high iodine–chlorinity ratio.

(3) DISCUSSION

SUGAWARA and TERADA (1957) showed that the relative amounts of the iodine forms present in each sample did not change with storage times of up to six months. They obtained the same results with stored samples as they did with samples treated at the time of collection. Duplicate analyses of stored samples by the authors at intervals as great as one year after the time of collection showed no change in the total iodine or the iodate–iodine values. These two observations suggest that the values reported in Table I represent *in situ* conditions.

The method of analysis used by SUGAWARA and TERADA detected iodide, since they used silver nitrate to concentrate the iodine. Their method complements the amperometric method, which responds to iodate. Near 50 °N. in the Pacific, SUGAWARA and TERADA found that iodide accounted for 20–80 per cent of the total iodine, with an average value for four complete stations (OS–1, OS–2, OS–44, OS–48) of 49·8 per cent. The amperometric method shows values which, computed as iodate, account for approximately 50 per cent of the total iodine with a range of 32–65 per cent. These findings strongly suggest that iodide and iodate are in fact the forms which are present. It must be added, however, that despite the qualitative agreement mentioned above, the absolute amounts of iodine found by SUGAWARA and TERADA are less than those detected by either the amperometric or the catalytic methods. The maximum total iodine concentrations reported by SUGAWARA and TERADA amounted to about 55 γ/L while a mean value for their results for samples below 200 metres at latitudes near 50 °N. would be about 45 γ/L, as compared with a mean value for the amperometric and the catalytic methods of about 64 γ/L for deep samples generally.

The results presented in Table I show that the iodate content of waters of the Northeast Pacific does not vary greatly with either depth or location, while the iodate content of the Arctic samples varies markedly. In the Arctic, however, the iodate distribution correlates strikingly with the density structure; large gradients in the iodate concentration tend to occur where large density gradients are present. The forms of iodine which are present are governed by processes which vary with depth in the Arctic to much greater extent than is the case in the North Pacific. What these factors are which govern the oxidation state of iodine in the ocean is not yet clear. It is evident that iodine is not in thermodynamic equilibrium, since iodate is rarely the only form which is present. The observed stability of the forms of iodine in stored sea-water samples implies that bacteria do not modify the iodine significantly. It seems clear that the biological uptake and regeneration of various forms of iodine, together with the ways in which iodine enters the atmosphere, must be studied before the distribution of oceanic iodine in its various oxidation states can be understood.

The distribution of total inorganic iodine in the sea appears to be less complex; Table I shows that the iodine is in constant ratio to chlorinity except in regions where phytoplankton, and particularly the larger benthic algae, are active and where differential biological concentration can modify the iodine–chlorinity ratio sig-

Table 1. *Oceanographic and chemical data. Station* 1. *25th July* 1956
49° 56′ N 139° 52′ *W*

Depth (m)	Cl‰	γ IO_3 − I/L	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
0	18·07	—	76	—	4·20	—
10	18·06	—	53	—	2·93	—
19	18·10	—	58	—	3·20	—
29	18·13	—	59	—	3·26	—
49	18·17	—	52	—	2·86	—
73	18·18	—	52	—	2·86	—
97	18·20	—	51	—	2·80	—
146	18·65	—	67	—	3·60	—
195	18·72	—	57	—	3·06	—
292	18·78	—	59	—	3·14	—
291	18·77	—	65	—	3·47	—
485	18·88	—	65	—	3·47	—
729	18·96	—	56	—	2·93	—
970	19·02	—	64	—	3·33	—
1456	19·08	—	61	—	3·20	—
1940	19·12	—	66	—	3·47	—
1945	19·13	—	70	—	3·66	—
1958	19·13	—	65	—	3·40	—
1963	19·13	—	65	—	3·40	—
2452	19·16	—	65	—	3·40	—
2931	19·17	—	65	—	3·40	—
2936	19·17	—	70	—	3·67	—

*values obtained by means of the catalytic method.
**Values obtained by means of the amperometric method.

Table 1 (*continued*). *Station* 2. *29th July* 1956. 44° 05′ *N*. 140° 04′ *W*.

Depth (m)	Cl‰	γ IO_3 − I/L	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
0	18·26	—	64	—	3·53	—
10	18·25	—	63	—	3·47	—
20	18·27	—	55	—	3·00	—
30	18·29	—	60	—	3·27	—
49	18·35	—	59	—	3·20	—
73	18·36	—	59	—	3·20	—
97	18·39	—	56	—	3·06	—
146	18·66	—	50	—	2·74	—
193	18·78	—	63	—	3·34	—
290	18·78	—	59	—	3·13	—
283	18·77	—	64	—	3·40	—
471	18·82	—	62	—	3·26	—
709	18·93	—	60	—	3·20	—
953	19·01	—	65	—	3·40	—
958	19·01	—	60	—	3·14	—
1434	19·09	—	67	—	3·54	—
1917	19·15	—	65	—	3·40	—
1928	19·15	—	62	—	3·26	—
1940	19·15	—	62	—	3·26	—
1949	19·15	—	62	—	3·26	—
2429	19·18	—	62	—	3·26	—
2914	19·19	—	62	—	3·26	—
2919	19·18	—	62	—	3·26	—
3399	19·19	—	62	—	3·26	—
3898	19·19	—	66	—	3·46	—
3903	19·19	—	60	—	3·13	—

Table 1 (*continued*). *Station* 3. 12*th August* 1956. 40° 01′ *N*. 134° 54′ *W*.

Depth (m)	Cl‰	γ $IO_3 - I/L$	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
0	18·49	—	62	—	3·33	—
10	18·48	—	62	—	3·33	—
19	18·48	—	62	—	3·33	—
29	18·39	—	56	—	3·06	—
47	18·27	—	54	—	2·93	—
71	18·27	—	52	—	2·86	—
95	18·27	—	54	—	2·93	—
142	18·42	—	50	—	2·74	—
190	18·66	—	57	—	3·07	—
286	18·78	—	60	—	3·20	—
287	18·79	—	56	—	3·00	—
482	18·81	—	60	—	3·20	—
727	18·91	—	58	—	3·17	—
970	19·02	—	63	—	3·34	—
977	19·01	—	64	—	3·40	—
1452	19·09	—	57	—	3·00	—
1940	19·14	—	63	—	3·26	—
1865	19·13	—	56	—	2·93	—
1874	19·13	—	61	—	3·20	—
2343	19·16	—	64	—	3·33	—
2818	19·17	—	65	—	3·20	—
2822	19·17	—	61	—	3.40	—

Table 1 (*continued*). *Station* 4. 25*th July* 1957. 50° 16′ *N*. 132° 43′ *W*.

Depth (m)	Cl‰	γ $IO_3 - I/L$	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
0	17·78	41	—	—	—	—
9	17·78	—	—	60	—	3·37
24	17·82	38	—	—	—	—
48	18·04	—	—	58	—	3·36
71	18·14	38	—	—	—	—
95	18·25	—	—	60	—	3·29
143	18·59	41	—	—	—	—
192	18·76	—	—	57	—	3·03
290	18·81	38	—	—	—	—
388	18·85	—	—	61	—	3·24
486	18·88	35	—	—	—	—
582	18·92	36	—	—	—	—
584	18·92	—	—	62	—	3·28
681	18·96	—	—	65	—	3·42
779	18·98	36	—	—	—	—
873	19·01	—	—	64	—	3·37
973	19·02	42	—	—	—	—
1069	19·04	—	—	62	—	3·24
1164	19·06	40	—	—	—	—
1256	19·08	—	—	65	—	3·40
1350	19·09	39	—	—	—	—
1449	19·11	—	—	66	—	3·46
1548	19·12	36	—	—	—	—
1748	19·14	—	—	62	—	3·24

Table 1 *(continued). Station* 5. 26*th July* 1957. 50° 51′ *N*. 135° 50′ *W*.

Depth (m)	Cl‰	γ IO_3 − I/L	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
10	17·99	30	—	66	—	3·67
50	18·08	34	—	60	—	3·34
99	18·10	31	—	54	—	3·29
198	18·74	30	—	60	—	3·21
396	18·83	32	—	66	—	3·51
596	18·93	33	—	62	—	3·28
678	18·96	38	—	62	—	3·26
875	19·01	36	—	60	—	3·16
1072	19·05	38	—	66	—	3·45
1268	19·08	35	—	62	—	3·24
1464	19·10	34	—	66	—	3·46
1760	19·13	34	—	69	—	3·61

Table 1 *(continued). Station* 6. 30*th July* 1957. 52° 43′ *N*. 154° 22′ *W*.

Depth (m)	Cl‰	γ IO_3 − I/L	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
0	18·13	28	—	60	—	3·31
10	18·12	28	—	55	—	3·04
25	18·14	27	—	57	—	3·14
75	18·20	28	—	59	—	3·24
150	18·65	34	—	60	—	3·50
299	18·86	29	—	62	—	3·29
499	18·94	25	—	67	—	3·51
596	18·97	29	—	64	—	3·37
794	19·02	30	—	61	—	3·21
992	19·05	33	—	67	—	3·52
1191	19·08	35	—	67	—	3·52
1390	19·11	32	—	67	—	3·52
1588	19·13	31	—	62	—	3·24
1788	19·14	30	—	—	—	—

Table 1 *(continued). Station* 7. 31*st July* 1957. 52° 38′ *N*. 158° 41′ *W*.

Depth (m)	Cl‰	γ IO_3 − I/L	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
0	18·14	28	—	51	—	2·82
10	18·14	29	—	59	—	3·25
25	18·15	28	—	55	—	3·03
50	18·17	28	—	58	—	3·20
100	18·37	28	—	54	—	2·94
124	18·60	—	—	62	—	3·34
149	18·74	32	—	57	—	3·05
174	18·78	—	—	60	—	3·20
199	18·80	29	—	64	—	3·40
249	18·84	—	—	58	—	3·08
298	18·86	27	—	60	—	3·17
299	18·86	27	—	61	—	3·23
399	18·90	—	—	62	—	3·28
499	18·94	26	—	67	—	3·54
598	18·97	—	—	66	—	3·48
698	19·00	23	—	64	—	3·36
798	19·02	29	—	69	—	3·63
898	19·03	—	—	64	—	3·37
997	19·06	29	—	60	—	3·16
1197	19·09	30	—	62	—	3·26
1496	19·12	32	—	63	—	3·31
1795	19·15	32	—	65	—	3·40

Table 1 (*continued*). *Station* 8. *2nd August* 1957. 52° 06′ *N*. 167° 40′ *W*.

Depth (m)	Cl‰	γ IO$_3$ − I/L	γ I/L		I/Cl × 10^6	
			*Cat.**	*Amp.***	*Cat.*	*Amp.*
0	18·07	—	58	58	3·21	3·21
10	18·07	—	61	59	3·38	3·28
24	18·06	—	58	56	3·22	3·12
39	18·08	—	58	55	3·21	3·04
58	18·10	30	—	—	—	—
77	18·18	—	59	64	3·24	3·52
97	18·29	26	—	—	—	—
121	18·45	—	59	58	3·19	3·16
146	18·68	28	—	—	—	—
170	18·75	—	65	61	3·47	3·26
194	18·78	32	—	—	—	—
293	18·84	—	65	68	3·46	3·62
298	18·86	26	—	—	—	—
398	18·90	—	67	63	3·55	3·33
497	18·94	30	—	—	—	—
597	18·98	—	62	64	3·26	3·37
697	19·00	21	—	—	—	—
797	19·02	—	64	65	3·36	3·42
897	19·04	27	—	—	—	—
997	19·05	—	64	63	3·36	3·32
1097	19·07	30	—	—	—	—
1197	19·08	—	65	66	3·41	3·46
1496	19·12	30	—	—	—	—
1796	19·14	—	61	59	3·18	3·07

Table 1 (*continued*). *Station* 9 (*East Sound, San Juan Archipelago*).
9th March 1957. 48° 38′ *N*. 122° 52′ *W*.

Locus	*Depth* (m)	Cl‰	γ IO$_3$ − I/L	γ I/L		I/Cl × 10^6	
				Cat.	*Amp.*	*Cat.*	*Amp.*
Mouth	0	16·72	—	47	—	2·80	—
	5	16·72	—	46	—	2·73	—
	10	16·76	—	45	—	2·66	—
	20	16·77	—	46	—	2·73	—
	30	16·76	—	45	—	2·66	—
	45	16·76	—	43	—	2·60	—
Middle	0	16·64	—	46	—	2·73	—
	5	16·67	—	45	—	2·66	—
	10	16·76	—	45	—	2·66	—
	15	16·79	—	43	—	2·60	—
	20	16·80	—	44	—	2·66	—
	25	16·79	—	44	—	2·66	—
Head	0	16·60	—	43	—	2·60	—
	5	16·60	—	43	—	2·60	—
	10	16·67	—	42	—	2·54	—
	15	16·70		43	—	2·60	—
	20	16·71	—	42	—	2·54	—

Table 1 (*continued*). *Station* 9 (*East Sound, San Juan Archipelago*). 25*th May* 1957. 48° 38′ *N.* 122° 52′ *W.*

Locus	*Depth* (m)	Cl‰	γ IO_3 − I/L	γ I/L		I/Cl × 10^6	
				Cat.	*Amp.*	*Cat.*	*Amp.*
Mouth	0	13·83	—	—	37	—	2·68
	5	14·79	—	(41)	39	(2·75)	2·64
	10	15·92	20	42	—	2·64	—
	20	16·49	—	46	48	2·79	2·91
	30	16·77	27	46	—	2·74	—
	45	16·91	—	46	47	2·72	2·78
Middle	0	13·14	—	—	—	—	—
	5	14·38	—	(39)	—	(2·71)	—
	10	15·18	—	40	—	2·64	—
	15	16·30	—	43	—	2·64	—
	20	16·79	—	—	—	—	—
	25	16·87	—	45	—	2·67	—
Head	0	13·80	—	—	—	—	—
	5	13·74	—	—	—	—	—
	10	15·50	—	42	—	2·71	—
	15	16·47	—	48	—	2·92	—
	20	16·67	—	66	—	3·96	—

Table 1 (*continued*). *Station* 10. 1*st March* 1958. 83° 30′ *N.* 155° 00′ *W.*

Depth (m)	Cl/‰	γ IO_3 − I/L	I/L γ		I/C × 10^6	
			Cat.	*Amp.*	*Cat.*	*Amp.*
5	16·40	0·0	—	57	—	3·48
25	17·28	8·6	—	58	—	3·36
50	17·28	29	—	58	—	3·36
75	17·77	26	—	62	—	3·48
100	17·98	25	—	62	—	3·45
150	18·41	25	—	61	—	3·31
200	18·92	47	—	58	—	3·07
300	19·21	46	—	63	—	3·28
500	19·29	64	—	62	—	3·21
1000	19·32	61	—	61	—	3·16
1500	19·34	46	—	61	—	3·16
2000	19·34	46	—	61	—	3·16

nificantly. Such biological activity can account for the observed variations in the iodine–chlorinity ratio at depths of 200 metres or less. Biological concentration of iodine is most evident in the inshore waters of the State of Washington, which abound in algae known to have a high iodine content; low iodine–chlorinity ratios result, except in one case where an unusually high iodine concentration very near the bottom may be due to decaying organic matter. Finally, the occurrence of high iodine concentrations in some surface samples may be explained by Closs' (1931) observation that oily parts of many marine organisms are rich in iodine.

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Consolidated slabs on the floor of the Eastern Pacific

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(*Received* 13 *April*, 1960)

Abstract—Tabular masses, largely phillipsite coated with manganese oxide, are abundant on the floor of the eastern Pacific. They appear to be remnants of layers of volcanic ash derived in large part from volcanoes within the basin. Some of the ash may correlate with the Worzel ash off Central and South America.

INTRODUCTION

SEMI-CONSOLIDATED angular tabular masses, or slabs, with areas of hundreds of square centimetres and thicknesses of a few centimetres are very abundant in large regions of the eastern Pacific Basin. The material in the slabs consists in large part of phillipsite and other alteration products but unaltered mineral grains in some places indicate a volcanic origin. Consideration of the possible sources and the history of the slabs may shed some light on sea floor processes.

SLABS IN THE NORTHEASTERN PACIFIC

The distribution of semi-consolidated slabs in the northeastern Pacific (Table 1, Fig. 1) is based on dredge hauls and bottom photographs. The noteworthy characteristics of the occurrence are the following :

1. The slabs are large, thin, relatively uniform in thickness, and commonly very angular (Fig. 2).
2. They are coated with a few millimetres to several centimetres of ferromanganese oxides, suggesting that they have been exposed on the sea floor for 10^4–10^5 years (Fig. 3).
3. They contain some unaltered minerals and fragments of volcanic glass but phillipsite and other alteration products are the most common constituents.
4. Slabs cover as much as 40 per cent of the bottom in some areas.
5. They appear to decrease in thickness to the west.
6. None of the slabs is on top of others.
7. Some slabs appear to lie in a reticulate pattern rather than being randomly distributed.
8. Manganese nodules cover much of the bottom between slabs in many places.
9. The nodules were formed after the slabs were deposited.
10. The fraction of the bottom covered by nodules and slabs varies systematically over an area of more than 10^6 km^2.

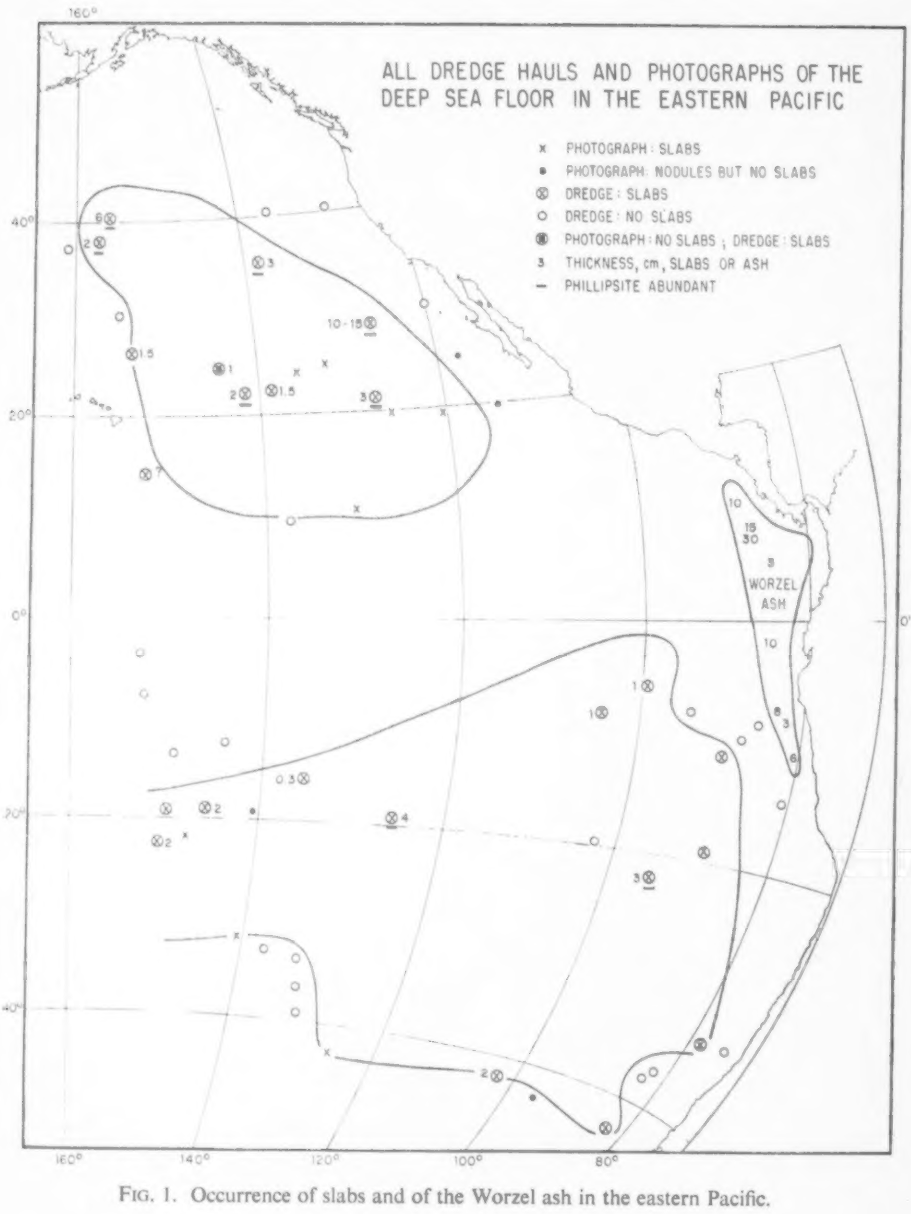
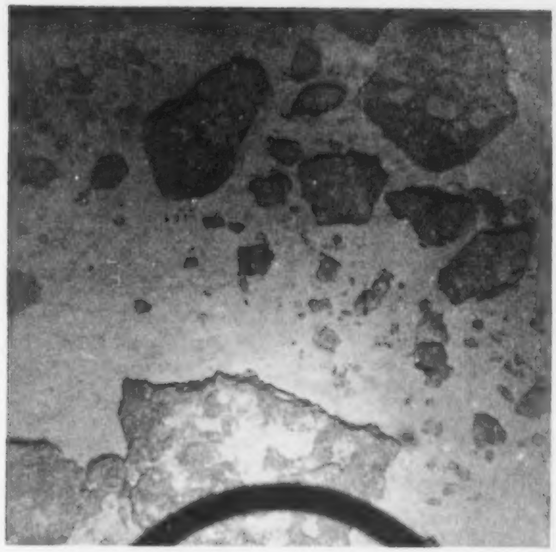
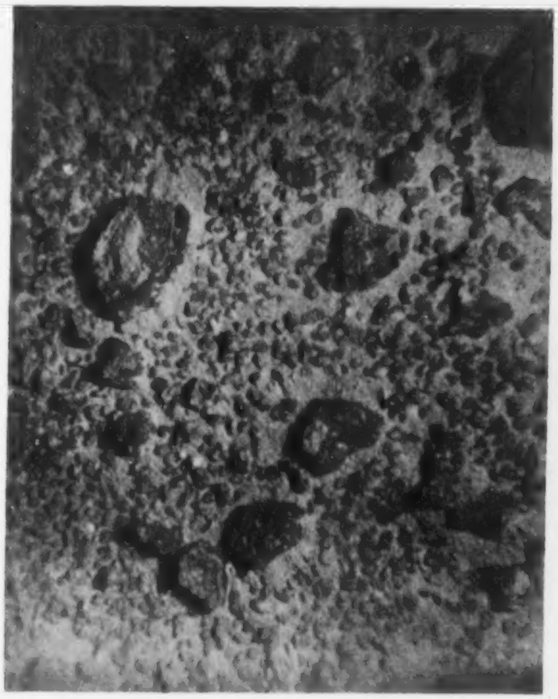


FIG. 1. Occurrence of slabs and of the Worzel ash in the eastern Pacific.



(a)



(b)

FIG. 2. Photographs of slabs on the sea floor of the northeastern Pacific.
(a) Naga 6 C. Photo by C. J. SHIPEK. (b) *Vitiaz* 4279. Photo by N. L. ZENKEVITCH. Note reticulate pattern of slabs. Abundant organisms around the slabs are visible on the stereo-pair of which this is one photo.

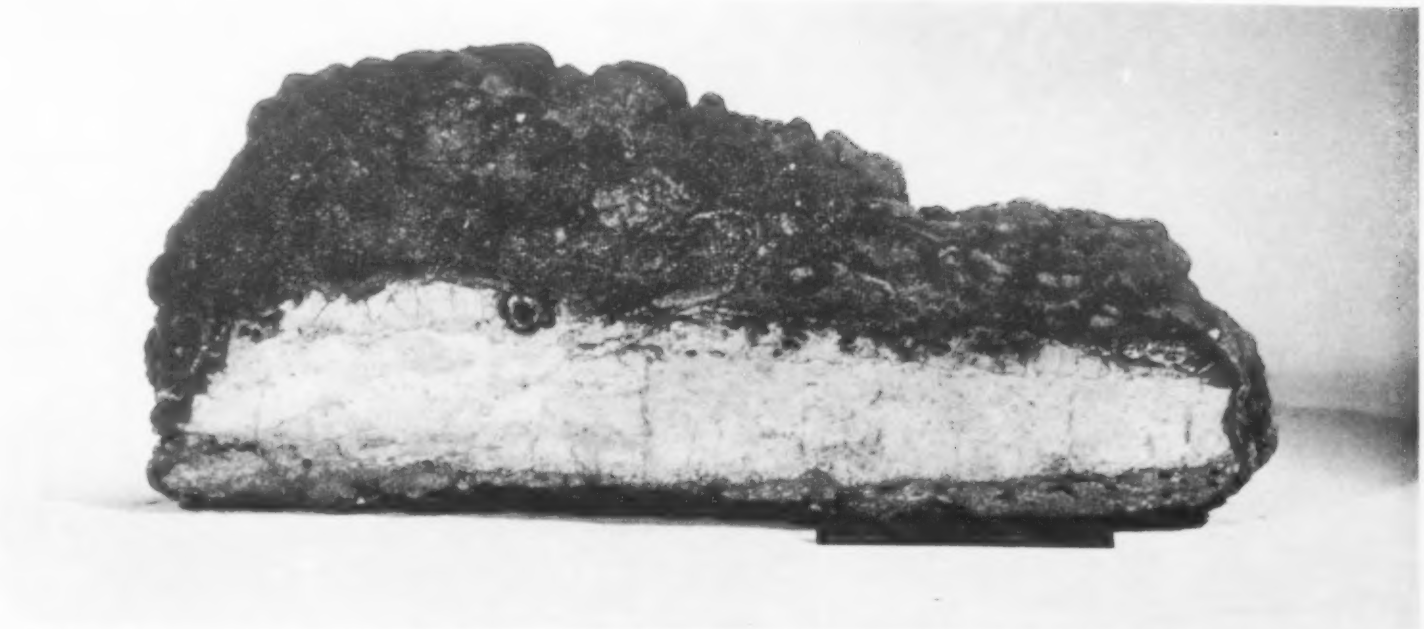


FIG. 3. Cross section of very large nodule from Northern Holiday C-10 showing abrupt termination of layer of phillipsite in nucleus, and thick coating of ferro-manganese oxides on top with thin coatings on bottom and sides.

ORIGIN OF SLABS

Two possible origins for the slabs may be considered : first, that they were emplaced as they now occur, and second, that they are remnants of a continuous layer. The first possibility requires that the slabs are altered blocks of pumice. Certainly pumice is now being distributed through much of the north equatorial Pacific where the slabs are found (RICHARDS, 1958) and the ferro-manganese crusts on top of large slabs contain small equi-dimensional pieces of pumice. However, pumice is very fragile and almost always is rounded by impact with other pieces in the throat of the volcano, in the air, or when floating on the wave-stirred ocean. Floating pumice is quite unlike the large, thin, angular slabs of the northeastern Pacific. Moreover, if the slabs are pieces of pumice, a random distribution with some pieces on top of others would be expected; and the apparent decrease in thickness toward the west and the regional variation in coverage of the bottom are unexplained. For these reasons it appears unlikely that the slabs are blocks of pumice.

All the features of the occurrence of slabs are explained if they are remnants of more or less continuous layers of altered ash. Ash layers vary in thickness systematically, and none of the fragments would lie on top of others. The angularity of the slabs indicates cracking by some physical-chemical process. Numerous dredge hauls show that unaltered ash layers, slabs of zeolites, and manganese nodules have layers with truncated edges and have been split in some way on the sea floor. After splitting or cracking, the edges sometimes are recemented to form septaria, but more commonly the edges are covered with a layer of ferro-manganese oxides, as much as several centimetres thick, thereby proving that some separation has occurred between adjacent slabs of cracked material. However, none of the adjacent angular slabs seen on bottom photographs can be matched as would be anticipated if they were fragments which formerly had been joined and simply moved apart. Consequently it appears that the material on one side of a crack is commonly removed or comminuted. The nuclei of small manganese nodules which are associated with the slabs, but at least in the northern equatorial Pacific, were formed later, may be fragments of the missing pieces of the ash fall.

Various mechanisms are capable of destroying a continuous layer on the sea floor, namely mass movements, erosion by currents, solution, and stirring by organisms, but only the last of these seems to explain the observations. Moreover the slabs themselves show evidence of biological stirring. 'Worm borings' cut through most slabs, and organisms as well as their trails, mounds, and burrows are visible on most photographs of slabs and manganese nodules. The organisms tunnel under slabs, circle them with trials, and stir up the sediment around them so that small manganese nodules do not form (Fig. 2).

The emplacement and fragmentation of the ash may be reconstructed as follows :

1. Where the ash was very thick the benthos was exterminated and no stirring occurred.
2. Where the ash was thinner and the benthos was large, as in the equatorial belt of rapid sedimentation (compared to red clay) the ash was thoroughly mixed but still detectable (ARRHENIUS, 1952).
3. In the areas of red clay, the scarcer benthos was almost exterminated even though the ash was only a few centimetres thick. Because of the very slow

Table 1. Occurrence of slabs on the sea floor of the eastern Pacific.

Station	Latitude	Longitude	Depth (m)	Description
Northeast Pacific				
Albatross 2	28–23 N	126–57 W	4340	Slabs 45 cm long, 15 cm thick, angular, many worm borings. Nucleus fairly pure zeolite partially replaced by ferro-manganese oxides, 1% oligoclase, volcanic glass, and magnetite. (1)
Challenger 253	38–09 N	156–25 W	5710	Slab 31 × 20 × 6 cm. Nucleus 2 cm thick, earthy with some zeolites. Annelid attached to bottom. (2)
Downwind BD-1	21–27 N	126–43 W	4300	Angular slabs to 31 × 24 × 5 cm. Some coated on all sides with a few mm of mn. Two layers, both with worm borings.
Downwind BD-2 P-2	10–25 N	130–35 W	4712	Photo shows slabs and spherical nodules partially buried. Only nodules dredged. Visible organisms. (3)
Naga 6 C	24–27 N	135–17 W	4300	Photos of angular flat slabs. No organisms or traces. (3)
Naga 8 C	23–17 N	138–15 W	4890	Slabs 3 × 5 × 2 cm. Nucleus 2 layers, earthy, 1·5 cm thick.
Naga 10 C	23–17 N	141–13 W	5400	Rounded slabs 3 × 4 × 2 cm. Nucleus almost pure phillipsite, 2 cm thick.
Northern Holiday C–10	40–14 N	155–06 W	5100	Slab 61 × 61 × 32 cm. Nucleus phillipsite 6 cm thick.
Vitiaz 3630	22–00 N	153–55 E	5733	Photo of sub-angular slab. Organisms, tracks and mounds abundant. (4)
Vitiaz 3632	17–38 N	154–54 E	5718	Photo of very abundant sub-angular slabs. Organisms and mounds. (4)
Vitiaz 4199	35–06 N	137–56 W	5035	Dredge haul. Slab 9 × 9 × 5 cm, angular. Nucleus 2 layers, earthy, in part vesicular, phillipsite abundant. Bottom layer 3 cm thick.
Vitiaz 4239	24–55 N	144–12 W	5190	Slab 7 × 7 × 3 cm. Nucleus 1 cm thick, red clay (?). Photo shows a few small nodules, organisms and mounds. (4)
Vitiaz 4249	24–55 N	132–18 W	4975	Slabs 7 cm long. Nucleus altered volcanic ash. (5). Photo shows small nodules on consolidated bottom. (4)
Vitiaz 4279	19–48 N	120–16 W	4104	Slabs encrusted on top with ferro-manganese oxides. Slabs of altered volcanic ash. (5). Photos of abundant slabs, organisms, and mounds. (4)
Vitiaz 4285	19–57 N	126–06 W	4545	Photo of angular slabs, mounds. (4)
Vitiaz 4370	26–12 N	153–44 W	6120	Slabs 4 × 4 × 2 cm. Thin ferro-manganese crust on earthy centre with abundant worm tubes. Quartz abundant, phillipsite rare.

Table 1—*contd.*

Station	*Latitude*	*Longitude*	*Depth (m)*	*Description*
Southeast Pacific				
Albatross 173	18–55 S	146–32 W	4460	Slabs 15 cm long, 4 cm thick, rounded. Palagonite tuff nucleus. (1)
Albatross 4662	11–14 S	89–35 W	4460	Nodules of ash and palagonite altered by and coated with ferro-manganese oxides. (1)
Albatross 4681	18–47 S	89–26 W	4390	Slabs 7·5 cm long. Nucleus of altered palagonite and clay. (1)
Albatross 4685	21–36 S	94–56 W	4040	Slabs 15 cm long, 3 cm thick. Volcanic ash slightly impregnated and coated with ferro-manganese oxides. (1)
Albatross 4717	5–10 S	98–56 W	3940	Flat nodules 2 × 2 × 1 cm. No concentric layering. (1).
Albatross 4721	8–08 S	104–11 W	3820	Flat nodules 2 × 2 × 1 cm.
Albatross 4736	19–00 S	125–05 W	4190	Slabs 20 × 10 × 4 cm of zeolites and palagonitic tuff coated with ferro-manganese oxides. (1) Broken on sea floor.
Challenger 280	18–47 S	149–52 W	3550	Nodules 5 cm long. Nucleus ' portions of the bottom ' perforated by worm tubes. (2)
Challenger 281	22–21 S	150–17 W	4370	Slab 45 × 30 × 7·5 cm. Nucleus 2 cm volcanic tuff with graded bedding above consolidated red clay. (2)
Challenger 300	33–42 S	78–18 W	2520	Slabs. Nucleus of hardened volcanic tuff. (2)
Challenger 302	42–43 S	82–11 W	2650	Large flat fragments.
Downwind HD-15	15–23 S	136–18 W	4480	Nodules 3 × 3 × 0·3 cm. Nucleus earthy.
Downwind HD-47	41–59 S	102–01 W	4200	Slab 20 × 10 × 3 cm. Top, ferro-manganese oxide crust 1 cm. Nucleus 2 cm volcanic ash, euhedral quartz and alcalic feldspar crystals to 1 mm diameter.
Downwind P-8	21–37 S	147–40 W	4684	Photo of slabs and spherical nodules capped with sediment. No visible organisms. (3)
Downwind P-10	32–08 S	140–30 W	4754	Photo of angular slabs and spherical nodules. Mounds produced by burrowing. (3)
Downwind P-11	42–50 S	125–32 W	4560	Photo of rounded slabs and smaller nodules. Organisms, trails and mounds abundant. (3)

(1) Murray and Lee (1909).
(2) Murray and Renard (1898).
(3) Photo by C. J. Shipek
(4) Photo by N. L. Zenkevitch.
(5) Personal communications (1960) N. S. Skornyakora and N. L. Zenkevitch.

rate of deposition, the ash was altered to zeolites and clay, partially cemented in some places, and cracked into angular slabs.

4. As the benthos repopulated the region, the more shattered and less cemented parts of the ash were stirred and ingested. Initially the process was random, but gradually the animals created micro-environments with thoroughly stirred small areas separated by vague lines of undisturbed residual slabs which continued to become harder and more coated with ferro-manganese oxides.

This sequence of events offers an explanation for the regional variation in the fraction of the bottom covered by manganese nodules and slabs which is otherwise puzzling. The occurrence of nodules at the sediment surface may be correlated with rate of sedimentation, but, if no other factors were important, a layer of abundant nodules would either be at the surface or buried. If a continuous ash layer, which would act as a locus for ferro-manganese deposition, were partially destroyed by organisms, the fraction of the bottom covered by ferro-manganese concretions would depend on the intensity of stirring by organisms. In the region under consideration, the abundance of the benthos probably is a function of the abundance of pelagic organisms in the surface water which provide food by sedimentation. The pelagic organisms vary in productivity with latitude and reach a peak near the equator which gives a positive correlation with the fraction of the bottom covered by slabs and manganese nodules.

SOUTHEAST PACIFIC SLABS

The evidence for a widespread occurrence of slabs in the southeastern Pacific is consistent although it is by no means as abundant as in the northeastern Pacific. No photographs are available, but ten of eleven dredge hauls in the region (Fig. 1) contain slabs. Several dredge hauls and photographs in the region of French Oceania show slabs, however; one slab is composed of coarse, graded, unaltered volcanic ash (Murray and Renard, 1891) indicating that it was derived from one of the many local volcanic islands. Most of the slabs in the large region to the east are on the East Pacific Rise which is covered with calcareous sediments. It is not known whether the slabs are at the sediment surface or are buried (but still accessible to the dredge). The high $CaCO_3$ content of these sediments results from slow solution on the bottom (Bramlette, pers. comm., 1959). The productivity of plankton in surface waters is not high as in the equatorial regions; indeed, it appears to be exceptionally low (Fisher *et al.*, 1958). Consequently this may be a region where few organisms would be available to stir an ash layer and where the ash would be buried more rapidly than in a region with red clay sediment. The volcanic ash slabs slightly impregnated with ferro-manganese oxides found at Albatross No. 4685 (Murray and Lee, 1909) (Table 1) may be typical of this environment.

SOURCE OF MATERIAL IN SLABS

More than one layer occurs in some of the northeastern Pacific slabs, and the thickness of ferro-manganese oxide coatings is quite variable suggesting different ages for the original ash layers. The decrease in thickness from east to west implies a source to the east. However the atmospheric circulation at the latitude of the ash deposit is entirely westerly and the ash cannot have been emplaced by falling vertically

through the ocean after lateral movement through the air. The only remaining possibility is lateral movement in the ocean which circulates in a pattern which could produce the gradient in ash thickness in this region. Only the top few hundred metres of the ocean move with appreciable velocity, and large lateral movement is possible only if the ash particles are small and only slightly denser than water. For an excess density of 0·1 gm/cc, 12 μ particles could be transported by surface currents throughout the northeastern Pacific. Ash particles of this character are not rare. The particles of oligoclase with a diameter of 0·15 mm found by CASPARI (*in* MURRAY and LEE, 1909) in slabs in this region cannot have been transported much more than 10 km, however. In sum, the ash was derived at least in part from the submarine volcanoes which are characteristic of the region (MENARD, 1955) and transported laterally by surface water currents.

In the southeastern Pacific also, some of the slabs were deposited as ash layers derived from near-by volcanoes. The slabs do not show any regional gradient in thickness and all may have local sources.

This investigation began as a search for the Worzel ash in the eastern equatorial Pacific. The ash has a relatively uniform thickness of 10 cm in the type region (WORZEL, 1959) and must extend over a much larger area (EWING *et al.*, 1959). The ash is buried under several metres of green mud in some places but in much of the northeastern Pacific, where sedimentation is very slow, it would be at or near the sediment surface. However, the distribution of the slabs, multiple layering and coarse texture in some places argue against the possibility that much of the material in the slabs is related to the Worzel ash.

Acknowledgements—The writer is indebted to M. N. BRAMLETTE, W. R. RIEDEL and E. D. GOLDBERG for critical discussions on the origin of the slabs and for identification of minerals in the slabs by optical and X-ray techniques. Unpublished photographs of the sea floor were made available by C. J. SHIPEK and N. L. ZENKEVITCH. *Vitiaz* samples were provided by P. L. BEZRUKOV, N. S. SKORNYAKOVA and N. L. ZENKEVITCH. Support was given by the Office of Naval Research under contract Nonr–2216 (01).

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SHORTER COMMUNICATION

Measurements of the California Current in March 1958

FEENAN D. JENNINGS* and RICHARD A. SCHWARTZLOSE†

(*Received* 25 *February* 1960)

Abstract—Two sets of drogues were placed approximately normal to the usual flow and followed for one and three days respectively. The first set, which extended thirty miles offshore, drifted southeastward. The second set, which extended from thirty to seventy miles offshore, also moved southeastward but with considerable variation in speed and direction along the line. In the latter set two rapidly moving streams appeared with a body of slower water between.

INTRODUCTION

DIRECT measurements of the California Current have been made at various times and with various techniques (REID, 1958; KNAUSS and REID, 1957; REID, RODEN and WYLLIE, 1958). As newer equipment has become available, especially radar and radar reflectors it has become possible to follow many drogues at one time and thus measure the currents over wider areas with only one ship. This paper describes the drogues used and the techniques followed on a cruise in March 1958 and presents the results of the measurements.

DROGUES

Drogues using a parachute as a sea anchor were used and described by VOLKMANN, KNAUSS and VINE (1956). The drogues used here were suspended from a bamboo pole some twenty feet long which was held up by an inner tube and counter-weighted to remain nearly upright. The parachute was attached to the pole at the inner tube by a ten metre wire. High on each pole was a light, a radar reflector, an orange flag, an identification number and a drift bottle (Fig. 1). It should be mentioned that in the first part of the survey the parachute was attached at the bottom of the pole. In high winds, this caused the pole to lean very close to the water surface, thus making it difficult to locate the drogue visually or by radar. Attaching a ten metre wire from the parachute to the water line alleviated this fault. The parachutes were in the upper portion of the mixed layer, which was about 60 metres deep as indicated from BT data.

POSITIONING AND LOCATING DROGUES

For a survey of this duration accuracy of navigation is of extreme importance. The position of the drogues on each run was determined from Loran and by radar observation of the coastline when the ship was within thirty miles of the coast. Further offshore the positions were determined from a combination of Loran and radar fixes from one drogue to the next and by extrapolation of the ship's courses and speed (dead reckoning).

Although the Loran receiver was in perfect operating condition, only one Loran system, 2-H-2, could be used with confidence in this region. This gave excellent positions as lines bearing 240° true from the coast, and was used to correct the southeasterly set of the ship by the current. Three other Loran systems could be received in this area but none of these was located to give satisfactory results in this area.

The radar was used extensively during the cruise, not only for locating the drogues, but also for positioning each drogue from the previous one, in a leap-frog fashion. Many times three or four

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drogues could be seen on the screen at one time and in these cases, the plotted positions were checked against each other for accuracy of positioning. By this method, the range and bearing indicators on the radar were shown to have very good accuracy. When two drogues became too far apart to position one from the other, a new drogue was put between the two. It is felt that the position of each drogue was accurately determined to within one mile of its true geographic position.

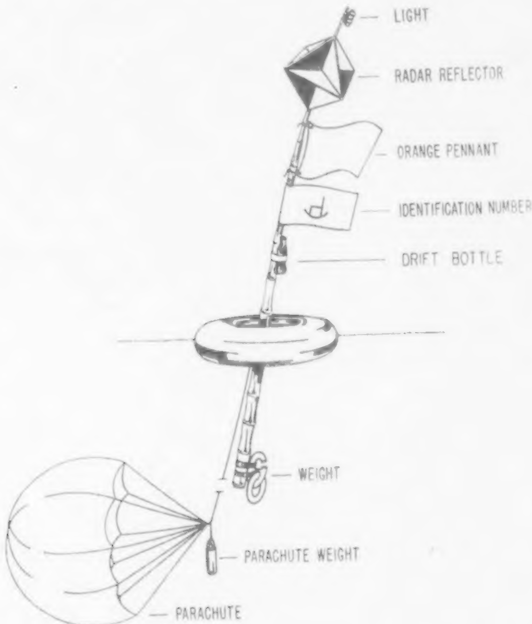

FIG. 1. Construction of the parachute drogue.

Some additional mention should be made concerning the effectiveness of the radar, which was a U.S. Navy type AN/SPS–5. The high degree of success of the entire survey was mainly due to the fine performance of this equipment. In calm weather, some of the drogues could clearly be located at distances up to nine miles. The usual range was between four and seven miles. Even in winds of ten to fifteen knots they still gave contacts at four to seven miles and in thirty knot winds, with the resultant heavy seas, the drogues were still being located and positioned at three miles.

SURVEY

On the morning of 19th March, in calm weather, fourteen drogues were set along a line bearing 240° from Pt. Pinos light, Monterey, from five miles to thirty miles from the coast. The two drogue closest to the coast were set by Scripps personnel from the R/S *Tage*. The *Tage's* personnel positioned these two plus the innermost drogue launched from USS *Thrasher*, until dark, at which time the *Tage* returned to port. The *Thrasher's* personnel spent the day, until 2200 hrs., positioning the outermost eleven drogues and during this time managed three complete runs along the line. The morning of the 19th began with winds from WSW at two knots. In the late afternoon the wind rose to fifteen knots from WSW. The wind continued to increase from late afternoon until the survey was no longer possible at 2200 hrs. At that time the wind was from the south at forty knots. The high seas and winds that developed during the night of the 19th severley disrupted the drogue pattern and only one of the fourteen was located afterwards. This was positioned from the shoreline along the coast at 1130 hrs. of the following day.

After the storm the drogues were set between 1900 hrs. March 23rd and 0700 hrs. March 24th. They were launched three miles apart between 30 miles and 100 miles from the coast along a line bearing 240° true from Pt. Pinos light. During the next three days, six positioning runs were made along the line. At three places along the line of drogues a group of three drogues were tied together, 1000 yards apart, with sixty thread cotton seine twine. This was done to determine whether drogues, tied in this fashion, would react to the currents differently to the individual drogues.

Of the 34 drogues launched, 31 were still being positioned after a period of 13 hours, 27 after 38 hours, and 22 after 63 hours. The maximum distance travelled by any drogue during the survey was 40 miles. Nine of them traversed more than 25 miles.

The wind from the evening of March 23rd through the morning of March 26th was from WSW, eight to ten knots and by 2100 hrs. it was from the south, 35–40 knots. At this time disintegrating radar reflectors on the drogues, the high seas and rain squalls made it impossible to find the drogues.

The effect of the wind on the radar reflector, flag, number board, bamboo pole and inner tube assemblage has been measured by DAN BROWN. With this information and the data on the drag force of parachutes from VOLKMANN, KNAUSS and VINE (1956), the effect of the wind (March 23rd—26) on the drogue was calculated to have been 0·02 knots, an insignificant amount. Only during the last four to six hours of the survey was the wind strong enough to affect the drogues a measurable amount. During the last few hours of the survey the wind was 35–40 knots, which affected the measured velocity of the drogues about 0·08 knots.

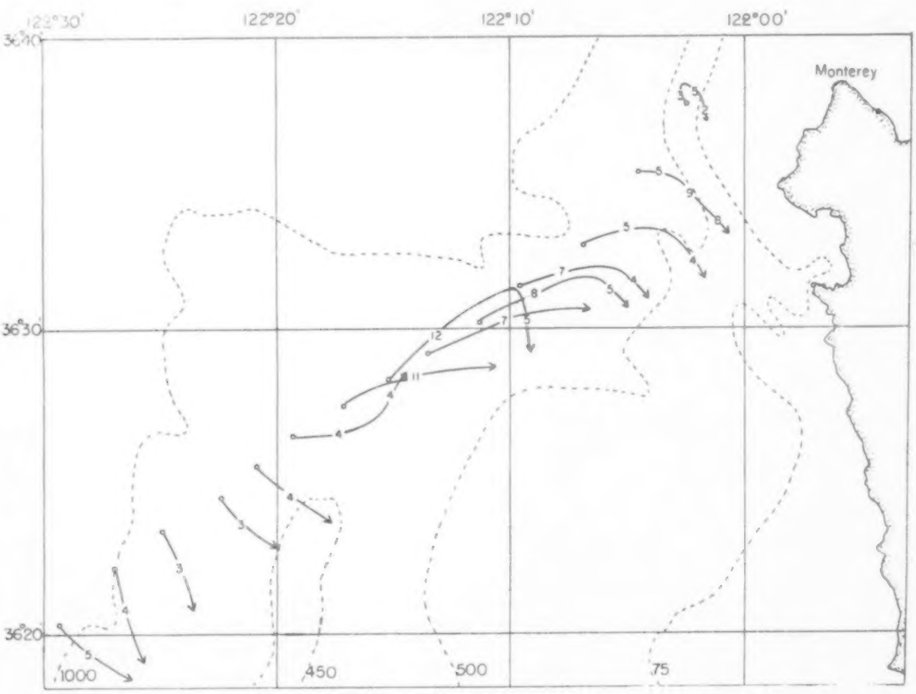

FIG. 2. March 19th, 1958, survey. The velocities are indicated in tenths of knots, and are plotted as the midpoint between the observed drogue positions of each run. Dashed lines are bottom depths in fathoms.

RESULTS

The drogues launched on 19th March were tracked for fifteen hours. The paths, taken by those drogues set within twenty miles of the coast, indicate that there may have been some influence by the tide. The movement of the drogues was to the east or southeast with speeds between 0·3 knots and 1·2 knots (Fig. 2).

The farthest offshore drogues, released 23rd–24th March, indicated that the flow was to the east. In the middle area were measured two streams at high speed with a slower moving body of water between, all moving southeastward (Figs. 3 and 4).

The current streams shown in Fig. 3 are the deduced paths of the individual drogues. The velocities are indicated by numbers, in tenths of knots, and are plotted approximately at the midpoint between the observed drogue positions of each run.

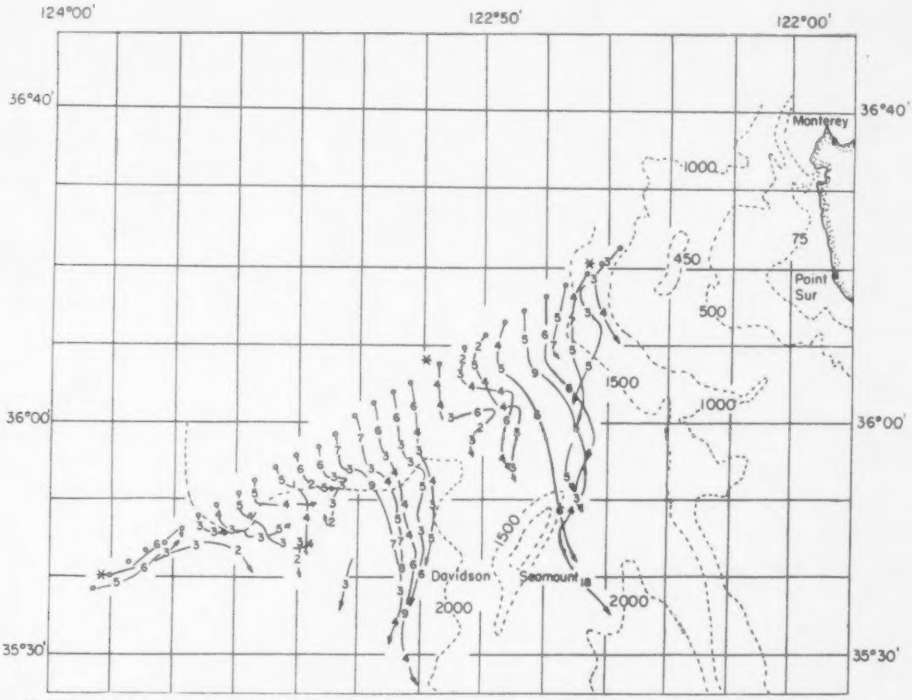

FIG. 3. March 23rd–26th, 1958, survey. The velocities are indicated in tenths of knots, and are plotted at approximately the midpoint between the observed drogue positions of each run. * denotes the positions where three drogues were tied 1,000 yards apart. Dashed lines are bottom depths in fathoms.

The development of the current pattern can be seen in Fig. 4, where the position has been plotted at constant time intervals. To derive the contours, the position was calculated for each drogue at noon and midnight of each day of the survey. Points of equal times were joined giving the distance each particle of water travelled during the twelve hour interval. The splitting of the current can plainly be seen in this figure as can the easterly flowing water at the west side of the pattern.

The average velocity of all drogues was about 0·5 knots. At the centre of the east stream, the average velocity over the 60 hour period was about 0·7 knots, while at the centre of the west stream, the average velocity over the same period was about 0·6 knots. The maximum observed velocity was 1·8 knots, which occurred late in the survey, at the centre of the eastern stream.

The reaction to the current on the three groups of drogues tied together was as follows :—

(1) The behaviour of each group seemed the same as the individual drogues in the same region.

(2) After one day, the three drogues in each group pulled together until they were less than 300 yards apart. They showed no tendency to remain lined up but assumed a random relationship to each other.

(3) After one and one-half days, one of the drogues was lost from each group. Only one of these strays was located again.

CONCLUSIONS

A detailed picture of a part of the California Current, during a period of a few days, has been obtained. These data are too particular to be compared usefully with the Atlas of Currents of the Northeastern Pacific Ocean (H.O. 570) which gives data averaged over larger areas and longer periods. Hydrographic casts were not made in the area this month. A detailed hydrographic survey in the same area at the same time, of such a cruise as this, would be of value in determining the relationship between the dynamic topography and direct current measurements.

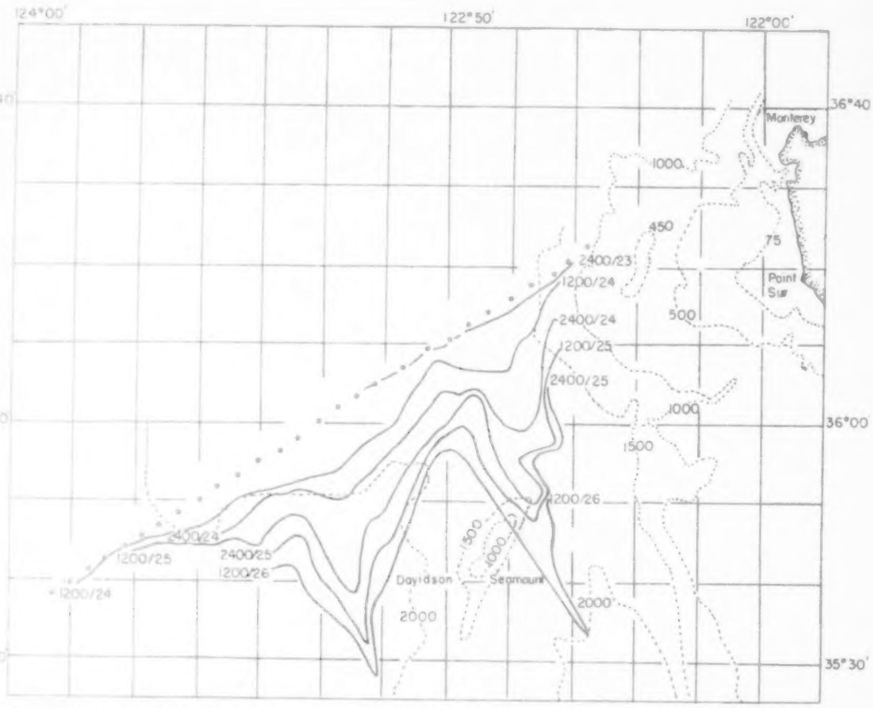

FIG. 4. March 23rd–26th, 1958, survey. The calculated distance each particle of water moved during a twelve hour interval. Dashed lines are bottom depths in fathoms.

It would be of interest to know whether the intensification of flow observed here near the coast, is a regular occurrence in March, and especially whether the two fast streams are part of a single one to the north which has been split by the Davidson Seamount.

The major immediate conclusion from this brief survey is that the technique is a very powerful one and that it will be possible to extend it to wider areas and over longer periods of observations, with no major changes in either equipment or method.

Acknowledgments—This paper represents one of the results of research conducted under the Marine Life Research Programme, the Scripps Institution's component of the California Cooperative Oceanic Fisheries Investigations, a project sponsored by the Marine Research Committee of the State of California; and research conducted for the Office of Naval Research under Contract Nonr 2216 (01). The authors are indebted to the U.S. Navy for supplying the USS *Thrasher* to conduct this research. The captain (Lieutenant C. J. LIMERICH) and crew are both to be thanked for their excellent cooperation and navigation. For the inshore work, the Hopkins Marine Station supplied its small boat the R/S *Tage*. Captain J. BALESTERI and technician B. FINKS were most helpful. From the Scripps Institution of Oceanography, the Programme Director of Marine Life Research, Professor

JOHN D. ISAACS, was one of the initiators of this survey and his advice and assistance has been most helpful. Also from Scripps, J. L. FAUGHN, D. M. BROWN and C. D. JENNINGS assisted greatly in gathering this data; J. L. REID, Jr. and GARTH I. MURPHY have read the manuscript and offered helpful suggestions.

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Contribution from the Scripps Institution of Oceanography.

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INSTRUMENTAL NOTES

R/V *Vema* Deep-Sea Winch

(*Received* 3 *September* 1959)

Abstract—Various types of deep-sea winches have been used aboard oceanographic vessels. Their design has been limited to use of electrically powered drums and winding engines utilizing rather elaborate speed regulation and braking devices, and of diesel-driven winches utilizing multi-ratio geared transmissions for hauling and the engine itself for braking. These winches have been able to lower cable at rates of 50–80 fathoms (100–150 m) per minute and to hoist at rates of 25–40 fathoms (50–75 m) per minute.

The recently redesigned heavy trawl winch being used aboard the R.V. *Vema* of the Lamont Geological Observatory (Columbia University) is described herein. During the lowering operation a Parkersburg Hydrotarder is used for braking. It provides a varying positive braking action functioning as a water brake which converts the mechanical energy into heat. For raising, a diesel engine drives the winch through a torque converter. This permits full utilization of the developed power of the engine, a method of exerting a fixed tension when pulling the apparatus out of the bottom, and eliminates the necessity of shifting gears and engine lugging (running over-loaded at slow speed) as with geared transmissions. With the new equipment, cable lowering speeds of 120 fathoms (220 m) per minute and raising cable speeds of 50–70 fathoms (100–130 m) per minute are possible.

INTRODUCTION

THE R.V. *Vema* acquired by the Lamont Geological Observatory in 1953, was fitted with a deep-sea trawl winch on deck, used for trawling, dredging and deep-sea sediment coring operations. This winch, built by the Lidgerwood Manufacturing Company, was originally designed to be diesel-powered through a geared transmission. To survive the hard usage many modifications of the original winch have been necessary during the past five years, until little is left but the base and framing.

A piston pump was originally connected to the drive shaft to use as a braking device during lowering, with its regulation controlled by adjusting the flow from the pump. As this method was unsuccessful, the engine, by means of a reversing gear, was then used as a brake. This procedure had two distinct disadvantages. (1) Since the engine ran ' free ' there was excessive carbon deposition and undue wear. (2) The use of lower speed gears were required to develop sufficient starting torque to begin raising the apparatus. This did not permit utilization of full engine power, thus, extremely slow raising speeds as well as excessive engine wear due to lugging of the engine resulted.

Since a vessel must stop during deep-sea sampling operations, it is advantageous to lower and raise equipment as rapidly as possible. This requirement prompted the redesign of the lowering and raising power units of the winch.

DESCRIPTION

The winch (Fig. 1) is designed to handle a maximum instrument load of 2,500 pounds (1,200 k) under normal operating conditions. Drum storage for 35,000 ft (10,000 m) of $\frac{1}{2}$ in. (12·7 mm) wire is provided. For deeper lowerings, up to 15,000 ft (5,000 m) of $\frac{3}{8}$ in. (9·5 mm) wire can be added. The smaller wire is spliced to the $\frac{1}{2}$ in. (12·7 mm) wire and wound onto the drum from a storage reel below decks. In general 24,000 ft (8,000 m) of $\frac{1}{2}$ in. (12·7 mm) wire is kept on the winch. Engineering calculations were made with this assumption.

Since the amount of electrical power available aboard R.V. *Vema* is limited, a separate diesel engine drives the winch through a torque converter. The engine is used to handle equipment when lowering over the side and for the first few fathoms until the weight of the load and wire is sufficient

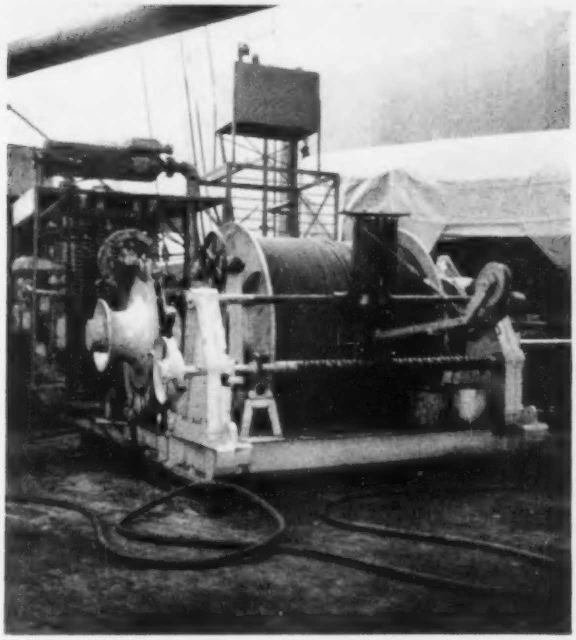

FIG. 1. R.V. *Vema* Deep Sea Winch. View shows accumulator springs, hand brake, storage and hauling reel holding 24,000 ft (6,000 m) of $\frac{1}{2}$ in. (12·7 mm) 6 × 19 improved plough steel cable. Tank over operator's cage is used as make up tank for Hydrotarder; it has since been lowered to make a more compact unit. In the right foreground are the level-winding mechanism and counting wheel.

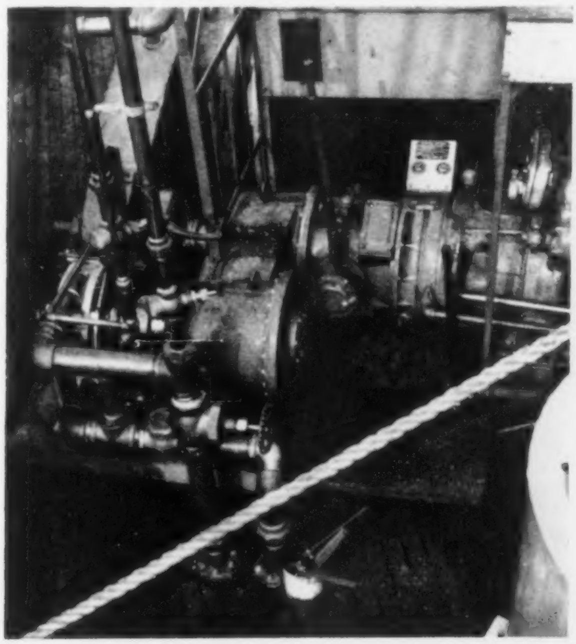

FIG. 2. Power and Braking Devices. Visible at extreme right is the 225 h.p. diesel engine, clutch, torque converter, reversing unit and reel drive. In the left foreground is Parkersburg brake and associated control valves.

to pay out without assistance. The major part of the lowering is done against a Parkersburg Hydrotarder brake. This permits high speeds with positive braking control.

The (storage) reel is supported by two roller bearings, one a spherical type (Fig. 1). The drum and accumulator springs are driven through a planetary gear system, the centre shaft of which passes through the drum to a large chain sprocket. The chain is driven in turn by a small chain sprocket mounted in line with the main power unit consisting of the engine, torque converter, reverse gear unit and hand brake.

The Hydrotarder brake is connected to the main power shaft by a chain sprocket. A cut-out type clutch is provided to disconnect the brake during raising.

A level winding attachment with a counting wheel to measure the amount of wire paid out, is located in front of the reel. A separate hand brake is attached to the reel; this permits control of the drum independent of the power drive or braking systems.

The controls for the Hydrotarder, engine, clutches and hand brake are mounted within easy reach of the operator (Fig. 2), in the protective cage which supports the make up tank for the Hydrotarder.

Two salt water pumps are located below decks to supply cooling water, the diesel engine and torque converter heat exchangers are mounted on the engine. The Hydrotarder heat exchanger on the other hand is located below decks and is connected by a pair of three inch pipes through which the fresh water is circulated. Throttle valves in this line regulate the flow of water from the Hydrotarder and so control the braking force. A system of valves permits proper adjustment of operating temperatures.

DETAILED DESCRIPTION

The engine used is a GM 6–71 diesel rated 225 h.p. (Detroit Diesel Engine Division of General Motors) and is rated for a maximum speed of 2,500 r.p.m. with the peak power delivered at 1,600–1,800 r.p.m. It is started electrically with batteries mounted below decks, which are charged through a d.c. charging circuit from the ship supply rather than a small generator mounted on the engine to avoid the salt water corrosion on deck.

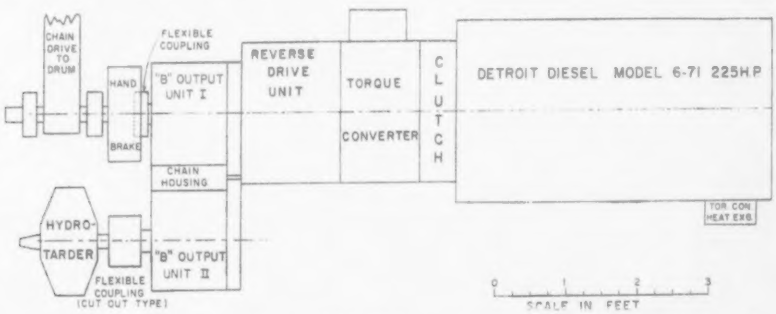

FIG. 3. Schematic drawing of power and braking portion of winch. The cut-out type flexible coupling permits the Hydrotarder to be disconnected during raising.

A three-stage hydraulic torque converter model CF–10019–TC–1 (Twin Disc Clutch Co.), delivers the power from the engine (Fig. 3). A two-faced self-adjusting dry clutch (Twin Disc Clutch Co.) is contained in the housing to disconnect the torque converter from the engine.

The distinct advantage of a torque converter over a geared transmission for delivering power from the engine to the reel is that at starting or stalled speed the output of the torque converter delivers five times the input torque. In addition it is possible because of the slipping action of the torque converter to apply full engine power by increasing its r.p.m. In starting a geared transmission against a dry clutch it is necessary to idle the engine while engaging the clutch and only a small fraction of the available engine power may be utilized.

After the initial starting load is overcome the torque required becomes less and as the output speed becomes more nearly equal to the input speed the torque multiplication becomes less. When the output is 70 per cent of the input speed, the ratio of output to input torque is unity (Fig. 4).

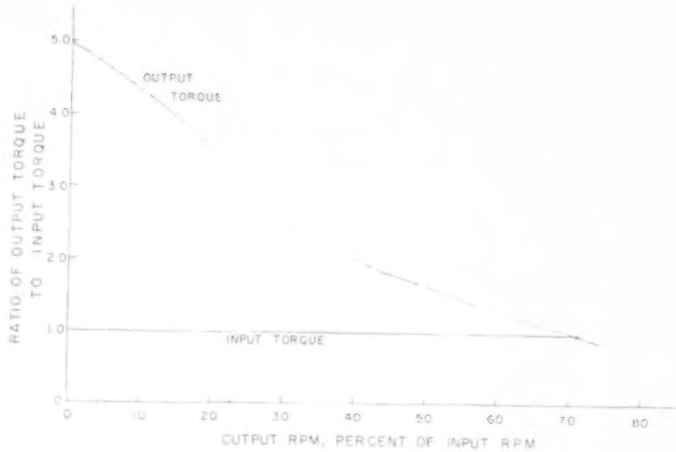

FIG. 4. Manufacturer's curve to show ratio of output torque to input torque as related to output vs. input speed of a three stage Twin Disc Torque Converter. Notice that at stalled or starting, a torque multiplication of five times is possible. The torque multiplication diminishes as output speed approaches that of input.

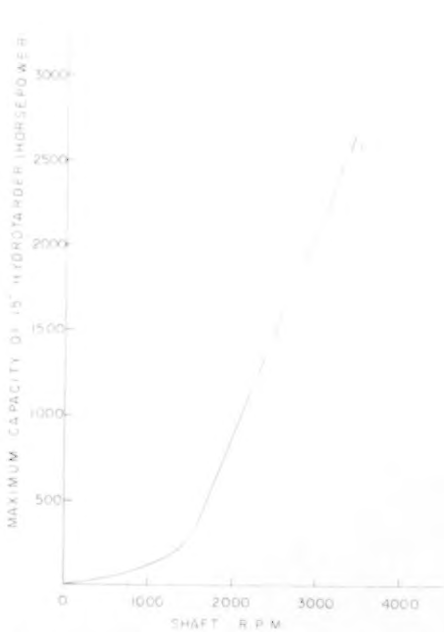

FIG. 5. Maximum braking horsepower of a 15 in. Single Rotor Parkersburg Hydrotarder as a function of r.p.m. Observe that greatest braking is possible beyond a rather noticeable break in the curve. For this reason the speed of the braking shaft has been increased to a value beyond the break.

A reverse drive unit Model RR–301 (Twin Disc Clutch Co.) is used on the output of the torque converter. It is necessary to have a reverse feature to handle loads on deck, to get equipment over the side and to lower the load to a sufficient depth so that the weight of the load and wire is adequate to pay wire off the reel without use of power.

Two ' B ' output housings (Twin Disc Clutch Co.) are interconnected by a chain and sprocket drive. Their function is to connect the power shaft to the braking shaft to which a Hydrotarder is connected. ' B ' output I is connected through a flexible coupling type 2–1/2 A (John Waldron Corp.) to the small chain sprocket which drives the reel. ' B ' output II is connected through a cut-out type flexible coupling (Poole Foundry and Machine Co.) to the Hydrotarder.

The Parkersburg brake is a 15 in. type ' B ' single rotor Hydrotarder (Parkersburg Rig and Reel Co.). The ratio of the chain sprockets 1: 1·33 permits the Hydrotarder to turn more rapidly than the small chain sprocket thus increasing its maximum braking horsepower (Fig. 5).

In addition to the speed of rotation, the braking action of the Hydrotarder depends on the amount of fluid it contains. The fluid (fresh water containing Prestone) acts as a deterrent to the rotor. This braking action in the Hydrotarder converts mechanical energy into heat. The fluid is then pumped below decks to a heat exchanger, cooled and returned to the Hydrotarder. Throttle valves regulate the amount of fluid flow.

To remove or add fluid to the Hydrotarder two quick-acting self-closing valves are used. The fluid is led to, and drawn from, the make up tank located on top of the operator's cage. For rapid unloading of the system a small stopcock is provided which introduces air into the system, as fluid is removed.

The reel is driven by a planetary gear system having a ratio of 7·5: 1. The opposite end of the planetary system is connected through a brake to a torque arm which operates the accumulator springs. The planetary system is driven by a shaft which is powered from the small chain sprocket, through a chain drive, having a ratio of 6·52: 1. The overall ratio between the small chain sprocket and the reel is 48·9: 1.

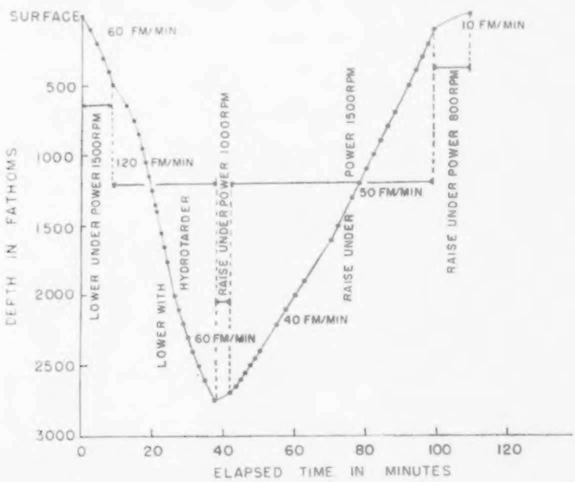

FIG. 6. A Typical Coring Operation. The length of time required (rail to rail) to lower to the ocean bottom and raise a piece of deep sea apparatus (weight about 1,500 lb.– 680 k). Average rail to rail time for complete lowering and raising operation is 35 minutes – depth 1,000 fathoms (2,000 m), 70 minutes – depth 2,000 fathoms (4,000 m) and 120 minutes – depth 3,000 fathoms (6,000 m).

The function of the accumulator springs is to keep relatively constant tension in the wire as the ship rolls and heaves. The compression of the springs is an indication of the tension in the wire. The spring calibration is indicated in a scale by an arrow attached to the springs. The calibration,

of course, changes with the amount of wire out because of the varying lever arm exerted by the wire about the reel. The correction is easily calculated and a chart showing this conversion is provided.

The level-wind is driven through a chain drive and worm gear by the reel. The drive contains a small reversing gear and dog clutch. This permits winding in either direction or hand winding by a small spoked wheel.

OPERATION

The utilization of the redesigned features of the R.V. *Vema* deep-sea winch has greatly reduced the length of time necessary for sediment coring operations, ocean bottom dredging and deep large volume water sampling. A standard rule of thumb, for the length of time required to lower and raise equipment (rail to rail) is: 35 minutes – water depth 1,000 fathoms (2,000 m), 70 minutes – water depth 2,000 fathoms (4,000 m) and 120 minutes – water depth 3,000 fathoms (6,000 m).

In one example (Fig. 6) 112 minutes were required to take a deep-sea sediment core in 2750 fathoms (5,100 m) of water. A standard piston coring apparatus weighing 1,350 pounds (650 k) was used on $\frac{1}{2}$ in. (12·7 mm) 6 × 19 improved plough steel cable. The beginning and end of the lowering operation were made at 60 fathoms (110 m) per minute, the major portion at 120 fathoms (220 m) per minute. After bottom contact the apparatus was raised slowly at 10 fathoms (18·5 m) per minute to avoid picking up the load abruptly and perhaps parting the cable. The major portion of the raising was made at 40–50 fathoms (75–90 m) per minute running the diesel engine at only 1,500 r.p.m. The last 100 fathoms (185 m) of wire was raised at 10 fathoms (18·5 m) per minute in the interest of safety.

The redesigned winch has been in operation, at this writing, from October, 1958 to June 1960 and has been used for over 500 deep-sea lowerings without incident.

Acknowledgements—The authors wish to thank Drs. MAURICE EWING, JOHN E. NAFE, and JACK OLIVER as well as the members of the Lamont Geological Observatory machine shop under the supervision of Mr. ANGELO LUDAS for their contributions to the project.

The research programme in which the trawl winch plays an important role receives support from the National Science Foundation, the Bureau of Ships and the Office of Naval Research, Department of the Navy.

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A seasonal mean sea-level indicator†

(*Received* 4 *January* 1960)

Abstract—By means of oil capillaries the indicator attenuates the tidal rise and fall of the sea surface, as well as all fluctuations of higher frequencies. The time constant of the response is chosen so that the smaller, slower fluctuation of sea level is transmitted with very little change of amplitude and

†Contribution from the Scripps Institution of Oceanography, New Series.

phase. There is no recorder. Visual readings of the oil level in a burette should be tabulated twice a week. Installation of the instrument is much easier and cheaper than a recording tide gauge.

INTRODUCTION

THE STUDY of day-to-day, or longer period, variation of sea level is usually carried out by making suitable averages of tidal data to eliminate the amplitude of the large tidal 'noise.' Such a method of elimination is generally known as mathematical filtering and has recently been refined to a high degree of accuracy by systematic computation of the most efficient weight factor averaging (GROVES, 1955). The instrument described here accomplishes essentially the same thing by an analog method. It consists of a two-stage low-pass hydraulic filter which attenuates the diurnal and semidiurnal tides to a negligibly small amplitudes while the long-term variations, say month to month, are transmitted with practically no attenuation or phase shift. Intermediate frequencies, such as the day-to-day variation, suffer a small attenuation and phase shift, according to the time constant of the instrument. The height of oil in a burette represents the mean sea level. The simplicity in taking the readings can be advantageous with untrained observers. Since the instrument does not respond to rapid fluctuations, a reading twice a week is adequate.

The installation of the mean sea-level indicator is very simple as compared to that of a tide gauge. There is the additional advantage that no subsequent data reduction is required. The instrument and its installation are not costly. These advantages, together with its simplicity of operation and reading, make the indicator suitable for use on any inhabited island or coast.

DESCRIPTION

The sea-level indicator (Fig. 1a) consists of a tube of small diameter, filled with sea water or with oil, running from the ocean to a manometer of heavy fluid (mercury). The manometer in turn is connected through two capillary tubes to two open, oil-filled standpipes.

Table 1. Relationship between the hydraulic and electrical parameters.

Hydraulic	*Electric*
$g\,\rho_w\,N_w$	E_1
$g\,\rho_0\,N_o$	E_0
R_1	R_1
R_2	R_2
$Am/g\,P$	Cm
$A_1/g\,\rho_o$	C_1
$A_2/g\,\rho_o$	C_2

$g \rightarrow$ *Acceleration of gravity*
$P = 2\,\rho_m - \rho_w - \rho_o$

The instrument can be represented equally well by an analogous electrical circuit (Fig. 1b). Potential differences in the electrical analogy correspond to pressure differences in the actual instrument; electric current corresponds to volumetric flow of fluid ($cm^3\,sec^{-1}$); and electrical resistance corresponds to hydraulic resistance. The latter is defined as the ratio of the pressure difference across a capillary to the volumetric flow through it. For a given capillary and given oil, this hydraulic resistance can be taken as constant if the resistance to viscous flow is much greater than the 'form resistance' or 'end effect.' (This condition is satisfied in the model described). Electrical capacitances are analogous to the capacitances of the various containers, i.e., mercury manometer and oil standpipes defined as the ratio of volume displacement to corresponding pressure change. Then, if the densities of sea water, mercury, and oil are ρ_w, ρ_m, ρ_o the resistance of capillaries R1, R2, the cross-sectional areas of the manometer and standpipes Am, A1, A2, the instantaneous height of sea level

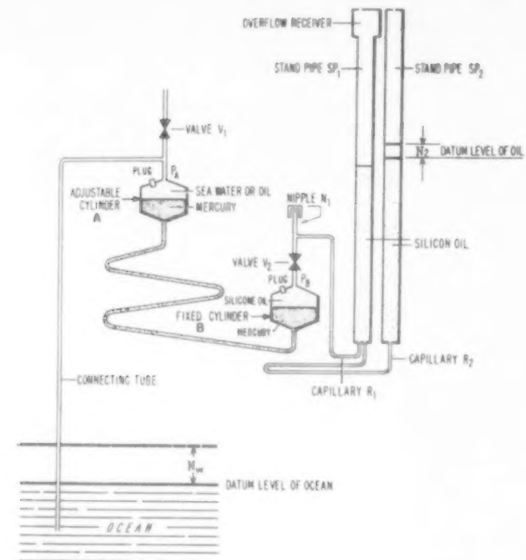

FIG. 1a. Schematic of the mean sea level indicator.

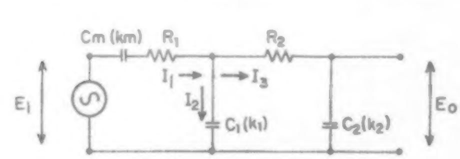

FIG. 1b. Electrical analogy.

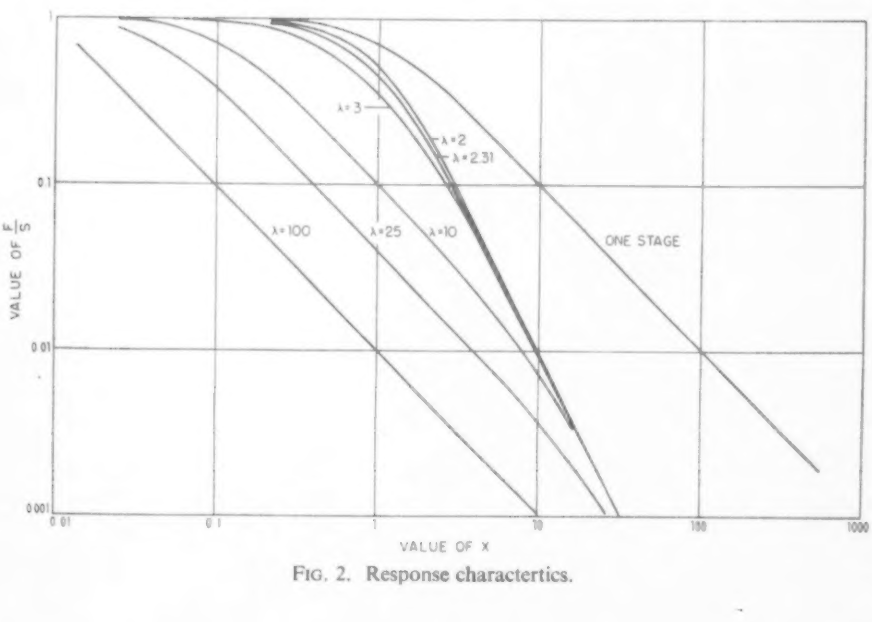

FIG. 2. Response charactertics.

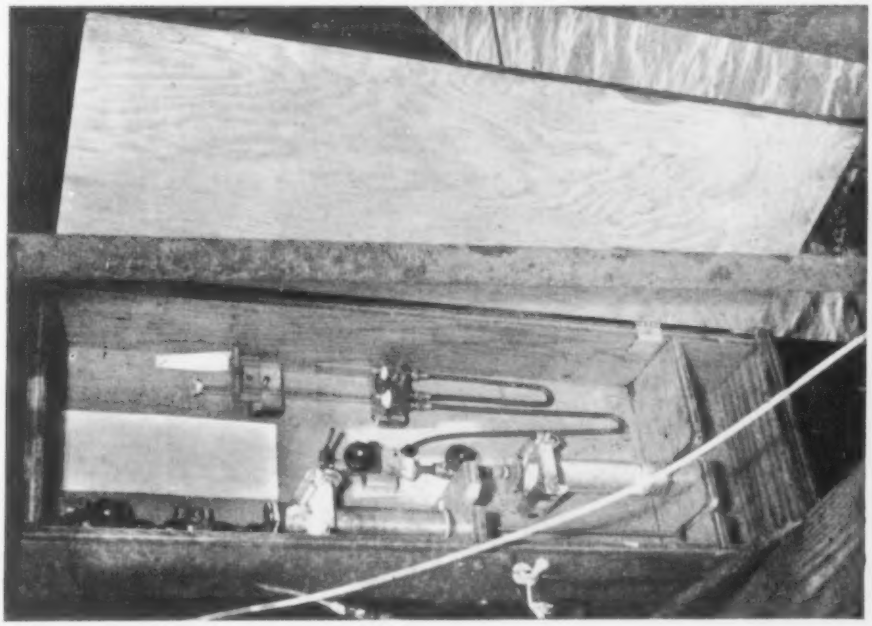

FIG. 3. Prototype of the mean sea level indicator in use at Scripps Institution of Oceanography, La Jolla. (The white plastic tube on the foreground does not belong to the apparatus).

N_w, and that of the oil in the second standpipe N_o above their mean positions, then the analogy between the hydraulic and electrical components shown in Fig. 1a and Fig. 1b is given in Table 1. A somewhat similar instrument for recording ultra low frequency ocean waves using a hydraulic and pneumatic filter has been satisfactorily used at Scripps Institution of Oceanography (MUNK, IGLESIAS and FOLSOM, 1948).

FREQUENCY RESPONSE

Writing Kirshoff's equations for the circuit of Fig. 1b gives

$$(Km + R_1)\, I_1 + K_2\, I_2 = Ei$$

$$I_1 = I_2 - I_3 = 0$$

$$-\, k_2\, I_2 + (R_2 + K_1)\, I_3 = 0$$

Solving for I_3 and replacing in the expression $E_0 = -\, K_2\, I_3$ yields :

$$E_0 = \frac{E_i}{\dfrac{Cm + C_1 + C_2}{Cm} - R_1 R_2 C_1 C_2\, \omega^2 + j\omega \left(R_2 \dfrac{C_1 C_2}{Cm} + R_1 C_1 + R_2 C_2 + R_1 C_2 \right)} \tag{1}$$

If F is the filter factor and ϕ the phase difference between E_0 and E_i we may write in a simplified parametric form

$$|E_0| = F\,|E_i| \tag{2}$$

$$F = S\,[(1 - X^2)^2 + \lambda^2 X^2]^{-\frac{1}{2}} \tag{3}$$

$$\tan \phi = -\, \frac{\lambda X}{1 - X^2} \tag{4}$$

with

$$S = \frac{Cm}{Cm + C_1 + C_2} \tag{5}$$

$$\Gamma = \sqrt{R_1 R_2 C_1 C_2 S} \tag{6}$$

$$X = \Gamma \omega \tag{7}$$

$$\lambda = \frac{Cm\,(R_1 C_1 + R_1 C_2 + R_2 C_2) + R_2 C_1 C_2}{Cm \sqrt{R_1 R_2 C_1 C_2}} \sqrt{S} \tag{8}$$

S is the sensitivity or asymptotic value of the filter factor for infinitely slow changes. It is noted that the filter factor and the phase difference are given by the three nondimensional numbers, S, λ and X, the latter being a nondimensional frequency. Therefore, the complete characteristics of the instrument is given by the three parameters, S, λ, and Γ, the latter having dimensions of a time constant. The function F/S is plotted as a function of X for various values of λ in Fig. 2. The one-stage curve is obtained as the special case when $Cm = \infty$ and $R_2 = 0$, $C_2 = 0$. The case of two identical stages $R_1 = R_2$; $C_1 = C_2$; $Cm = \infty$ gives the $\lambda = 3$ curve.

It is noted from Fig. 2 that the best cut-off characteristics are obtained from the smallest possible values of λ. If λ is too large, the two-stage instrument has little advantage over a one-stage instrument. It can be shown that λ can never be less than two. If we write

$$\frac{Cm}{C_1} = a \qquad \frac{Cm}{C_2} = b \qquad \frac{R_1}{R_2} = p \qquad (a, b, p, \text{all} > 0)$$

then

$$\lambda = \frac{p\,(a + b) + a + 1}{\sqrt{p\,(a + b + ab)}} \tag{9}$$

If we now hold a and b constant while minimizing with respect to p we find that the minimum value is

$$\lambda = 2\sqrt{\frac{(a+1)\,(a+b)}{a+b+ab}}$$

which occurs for $p = a + 1/a + b$ (11). This expression further minimized with respect to a and b requires $a + b + ab \gg a^2$ (12) from which the limiting value $\lambda = 2$ is obtained.

SELECTION OF DESIGN PARAMETERS

The choice of the sensitivity of the apparatus essentially depends upon two factors : the expected maximum range of seasonal sea level variation and the necessity for practical dimensions for the enclosing cabinet. For the latter we may accept one metre as the maximum desirable vertical dimension. Due to the uncertainty of the actual position relative to mean sea level at installation time and to the need to contain within the first standpipe the residual tidal oscillation, the range of significant oil level variation cannot be more than approximately one-third of the full standpipe length : thus 33 cm.

A sensitivity of one-third would then accommodate a variation of one metre in the mean sea level. Hence, we take $S = \frac{1}{3}$. It is convenient to take $a = b$ in order that both standpipes have the same diameter, in which case $a = b = 1$, $p = 1$ and $\lambda = 2\sqrt{4/3} = 2{\cdot}31$.

There is much to lose and only very little to gain by attempting to reduce λ further. This would suppose either reduction of S or choice of b significantly larger than a. The cut-off characteristic, however, would not be appreciably improved. The final choice of Cm C_1, C_2, depends upon the following considerations : We want the standpipes large enough to permit ease of construction and a flow of oil high enough to avoid an extremely small capillary; we also want these standpipes small enough to limit the cross sectional area of the manometer and thus reduce the required quantity of mercury.

If

$$A_1 = A_2 = 1 \text{ cm}^2$$

then

$$Am = \frac{2\rho m - \rho_o - \rho_w}{\rho_o} = 26{\cdot}7 \text{ cm}^2$$

The final choice of R_1 and R_2 is dependent upon the chosen cut-off characteristics. The choice is made from the curves of Fig. 2.

Table 2. Cut off characteristics.

$X = 18$	$T = \frac{1}{2}$ *day*	$\frac{F}{S} = 0{\cdot}0031$	*Residual for* 100 cm, *Semi-diurnal Tide* = ·1 cm
9	$T = 1$ *day*	0.0115	*Residual* for 100 cm, *Diurnal Tide* ·38 cm
4·5	2	0·046	
1·8	5	0·22	
0·9	10	0·49	
0·45	20	0·78	
0·30	30 *days*	0·89	

For $\lambda = 2{\cdot}31$ if we take $X = 9$ when ω corresponds to the diurnal tide, then we get for the passing band characteristics the values tabulated in Table 2. Monthly changes pass with a relative error in amplitude of $(1 - F/S)\,100 = 11\%$. Cutting at a lower frequency would reduce the tidal residue but increase badly the error in month-to-month variation. From the above selection

$$X = \Gamma\omega = 9$$

for

$$\omega = \frac{2\pi}{24 \times 3600} = 7{\cdot}26 \times 10^{-5}\, s^{-1}$$

we obtain

$$\Gamma = 1{\cdot}3 \times 10^5 \text{ sec}$$

since

$$R_2 = R_1; \quad S = \tfrac{1}{3} \quad \text{and} \quad C_2 = C_1 = \frac{A_1}{\rho_0 g} = 1{\cdot}05 \times 10^{-3} \text{ cgs}$$

then

$$R_1 C_1 = \tau = \frac{9\sqrt{3}}{\omega} = 2{\cdot}16 \times 10^5 s$$

$$R_1 = \frac{\tau}{C_1} = 2{\cdot}07 \times 10^8 \text{ cgs}$$

Poiseulles' law $R = 8\eta l/\pi r^4$ permits a preliminary choice of the capillary dimensions l and r, the length and inside radius, respectively. Because of the critical dependence of resistance on inside radius of a capillary, the capillaries should be experimentally adjusted to the accurate value of the time constant $\tau = 2{\cdot}16 \times 10^5$. Due to the very high viscosity of the silicone oil used (1000 cstk at 25° C) the capillary end effect is completely negligible.

CONCLUSION

A prototype of the mean sea-level indicator was installed at the end of the pier of the Scripps Institution of Oceanography, La Jolla, California, at the beginning of April 1959 and has worked satisfactorily ever since (Fig. 3). Fig. 4 shows the mean sea-level changes which have been obtained

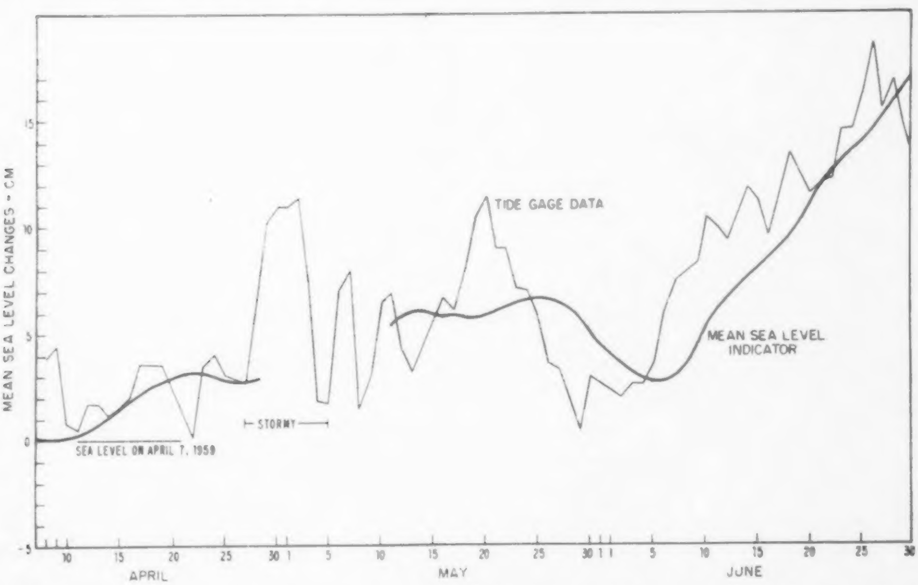

FIG. 4. Variation of the mean sea level at Scripps Institution of Oceanography, La Jolla from April 7 to June 30, 1959.
1. Fine line – according to processed data of the nearby tide gage.
2. Heavy line – from mean sea-level indicator.

both from the mean sea-level indicator and from the tide gage located a few feet away. The tube to sea is ¼ in. copper tube. The apparatus is 22 ft above lower low water. No air accumulation in the tube has been observed, and no fouling of the tube hole has interrupted its continuous running.

In case of limited attendance of such a station, it might be advisable to use oil in the tube to sea and to end it in a larger cylinder as shown on Fig. 5. Periodically, say every year, it might be advisable

to flow oil through the tube to eliminate any possible bubbles. This can be accomplished most easily by the method described in Fig. 6. The use of oil has also the additional advantage of increasing somewhat the maximum allowable installation height because of the lower density of oil and the lower vapour pressure of some available oils.

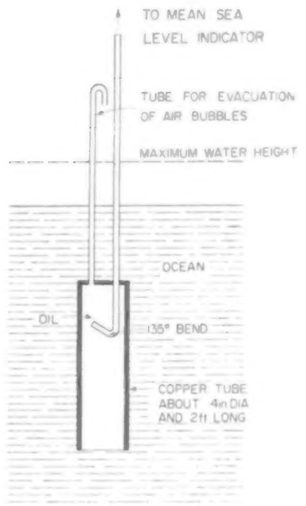

FIG. 5. End protection of the connecting tube against:
(1) Bubble access.
(2) Sediment plugging.
(3) Escaping of oil.

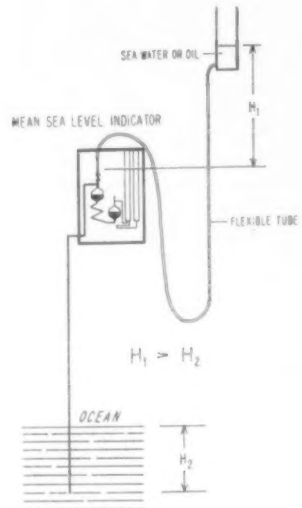

FIG. 6. Priming of the mean sea-level indicator.

A new version of the mean sea-level indicator (Fig. 7) has benefited from experiments with the prototype. Particular attention was taken to preserve a permanent datum level. This was solved by putting a container at the end of the standpipe 1 to receive and retain the oil without any overflow were air accidentally admitted in the sea tube. After reparation of the sea tube the apparatus is primed again; the oil and mercury volumes remain unchanged and the basic equilibrium is preserved. This precaution is particularly useful for records taken over a long period. For the same reason the dimensions of the apparatus must not change with time; this was taken into account in the final design.

APPENDIX

Installation, Starting and Tabulation of Readings

The instrument cannot be located higher than about 30 ft above the lower low water unless a lighter fluid is used in the tube connecting to the sea. The vapour pressure of water at 30 °C : 31 mm Hg or 4/100 of one atmosphere. Maximum theoretical height : $100 - 4/100 \times 76 \times 13{\cdot}6$ cm or $H_m = 30{\cdot}8$ ft (with light oil in the tube to sea $H_m = 34$ ft). This requirement eliminates the possibility of using the mean sea-level indicator in cases with an extreme tidal range. The cabinet has to be secured at a steady level, and the tube to the sea should dip enough so that its end is not uncovered in the trough of the deepest waves at the lowest tides. Due to the extremely slow response of the apparatus, a lot of time can be required at the start if a careful schedule and a definite procedure are not followed. There are two phases : filling and zeroing.

Filling.

Pour a few cubic centimeters of the mercury into cylinder B. Fill it with oil and put back plug P_B. Plug the upper end of the standpipe SP_1 and close the valve F_2. The nipple N_1 is capped. Pour

the balance of the mercury into cylinder A and replace the plug P_A. Open V_2. The oil is forced through the capillary R_1 into SP_1; it compresses the air above it and is forced into SP_2 through R_2. This requires several hours. When a few centimeters of oil appear in SP_2, close V_2. Unplug SP_1 (SP_2 is already unplugged). Pour oil into both SP_1 and SP_2 until they are half full $\pm\frac{1}{2}$ cm. Remove

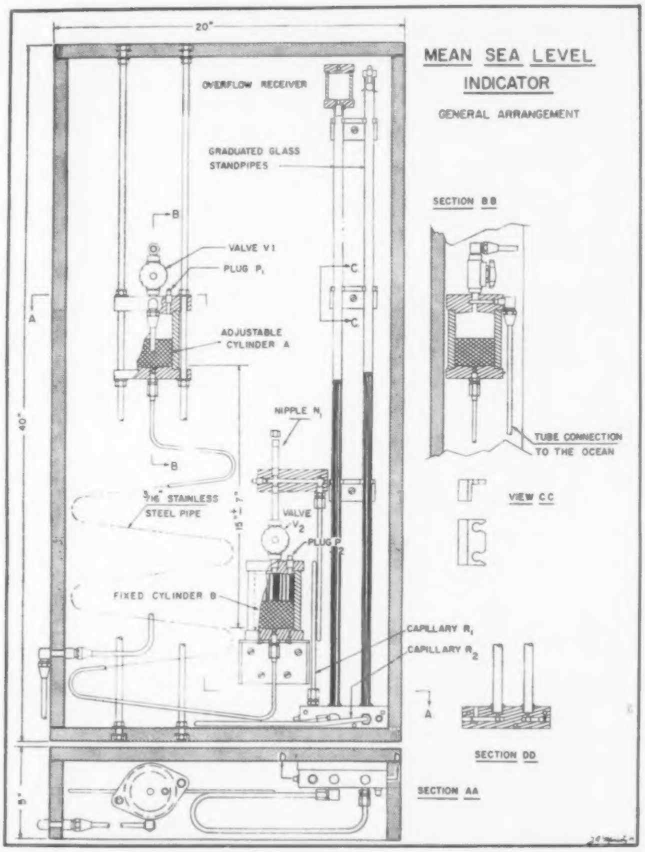

FIG. 7. Design of the final version of the mean sea-level indicator.

the cap of nipple N_1. Pass over a transparent plastic tube about 3 to 4 ft long. Open V_2. The oil flows out slowly under the manometer pressure. Close V_2 when the mercury levels in both A and B reach the marks (cylinders A and B are made of Plexiglas). Remove 8 or 10 cm of oil from the end of the plastic tube to make the interface between oil and air clearly visible. Hang tube end at top of cabinet.

Starting

Determine as accurately as possible the position of mean sea level. The following method is sufficiently accurate : Install a tide staff (pole with graduations). Make 3 readings at 8-hour, 16-min. intervals or better, 6 readings at 4-hr, 8-min. intervals smoothing by eye the waves if any and average them. This will give a sufficiently good approximation for the mean sea level; make a visible mark on the staff; determine the height of the apparatus above mean sea level and set up the cylinder A to the corresponding compensated height. Then prime the apparatus. The diagram in Fig. 6 illustrates one of the most suitable methods.

The following and last step has to be performed with the greatest care. The zeroing will then be easy, fast, simple; but any carelessness may lose many days and may necessitate further handling of oil and mercury. All valves are closed. The oil in both standpipes is half way up $\pm \frac{1}{2}$ cm. The tops of both standpipes are open. The apparatus is primed. Mark location of oil-air interface in the plastic tube.

Wait until the sea comes close to mean sea level, rising (or falling). When it is 30 cm below (or above), set up the oil level in the plastic tube 30 cm $\times S = 10$ cm below (or above) mean height of standpipe. Open valve V_2 and check the oil level in the tube. It should not move at first but slowly rises (or falls) as the tide comes up (or down). Elevate (or lower) the plastic tube to keep the oil level at the same place in the tube. As the tide height reaches mean sea level, close valve V_2 and note the height difference between the oil in the first standpipe and the oil in the tube: $+ \Delta l$ if oil level in tube is higher, $- \Delta l$, if lower.

NAME & LOCATION OF STATION					YEAR
Scripps Institution			La Jolla		1959
MONTH AND DAY	TIME	1 ST STAND PIPE	2ND STAND PIPE	H F R L R PHASE OF TIDE	OBSERVATIONS
Jan. 22	10-30 G.M.T	257	232	L	
" 24	10.15	252	232	FL	
" 26	11.00	251	231	F-	
" 28	10.30	251	230	H+	
" 30	10.30	254	231	RH	
Febr. 2	10.15	257	232	R+	

FIG. 8. Data sheet suggestion : it should include in addition to the basic data a reading of the first standpipe and an indication of the state of the tide.

If $|\Delta l| > \frac{1}{2}$ cm, the apparatus is sufficiently close to equilibrium and no further adjustment is required. If $|\Delta l| < \frac{1}{2}$ cm correct position of cylinder A. (Correction : opposite sign to Δl and equal $\Delta l\, \rho_0/\rho m - \rho w$). Valve V_2 must be reopened at high or low tide, after installing the cap on nipple N_1. This cap should be tightly sealed and never reopened; any leak or reopening would lose the datum.

For frequencies of the order of the tides the phase shift is close to π. The diurnal tide being much less attenuated than the semi-diurnal, reading the instrument at zero amplitude of the diurnal tide offers a way to increase the filter effectiveness. If such a schedule of the observation could be kept, this should be possible in several stations, it might be advisable to reduce the time constant τ by using shorter capillaries in order to extend the pass band to shorter period changes.

In any case a column should be reserved in the data sheet for entering the tide state at the time of every reading. Fig. 8 shows a suggested way to symbolize this data. Furthermore, meteorologic and sea-state observations might in many circumstances become very valuable in the interpretation of the data from the sea-level indicator.

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GORDON GROVES†

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Deep-sea free instrument vehicle

(*Received* 11 *April* 1960)

Abstract—A number of free instrument vehicles have been designed and tested. These are simple, reliable, inexpensive devices that transport recording instruments or sampling equipment to the deep-sea bottom, or to intermediate depth, and return them to the surface. Vehicles are provided with radar reflectors and other location devices. In the first tests the vehicles bore fish traps and were successfully operated to 2,000 fathoms. Other instruments designed to make use of the free vehicle's unique capabilities are under development.

INTRODUCTION

THE difficulty of measuring and sampling in deep ocean waters greatly limits the conduct of oceanographic research. Oceanographers traditionally have suffered from inefficiency in their operations because of their dependence upon conventional long-wire techniques for most deep measurements. Freely descending vehicles have been used on occasion (EWING and VINE 1938), (ISAACS and KIDD 1957). These have not previously been brought to the level of design that would allow their routine mass use as general purpose oceanographic tool, however.

Development of the Deep Free Vehicle (DFV) system was undertaken to overcome some of these difficulties, to permit the small vessel to participate in deep investigations, and to add versatility and effectiveness to the large vessel. As examples, with the DFV, small vessels without heavy winches can now be used to collect water samples and benthic organisms on the deep-sea bottom, and many deep-water investigations can be added to the expedition programme of large vessels.

Thus, an expedition with a heavy programme of piston coring or other operations necessitating long-wire techniques, can simultaneously obtain other related or independent measurements by the DFV technique, and small unspecialized vessels can engage in such studies as sampling water and organisms in deep atomic waste disposal areas.

GENERAL DESCRIPTION

In brief, the system (Fig. 1) consists of :

(1) a flexible plastic float filled with gasoline that provides positive buoyancy at any depth;

(2) a separate submersible marker buoy, which enables the system to be located when it arrives at the surface;

(3) a depressing ballast weight with a release device that releases ballast at a predetermined time or depth; and

(4) one or more recording or sampling instruments, whose point of attachment in the line is adjustable.

OPERATION

In operation, the system is launched freely from a ship. It descends to the bottom where it remains until the ballast weight is released. By use of the pressure release, the system can also be programmed to descend to an intermediate depth and return to the surface.

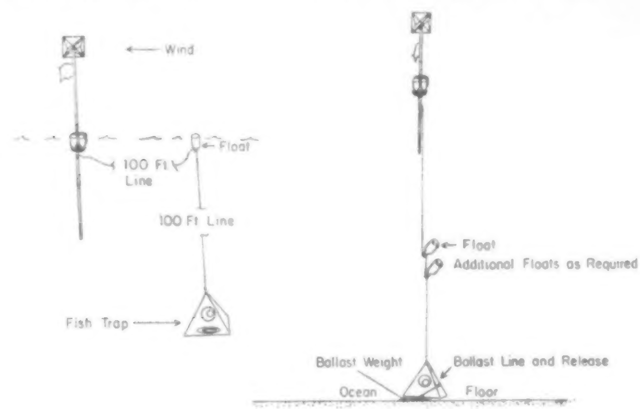
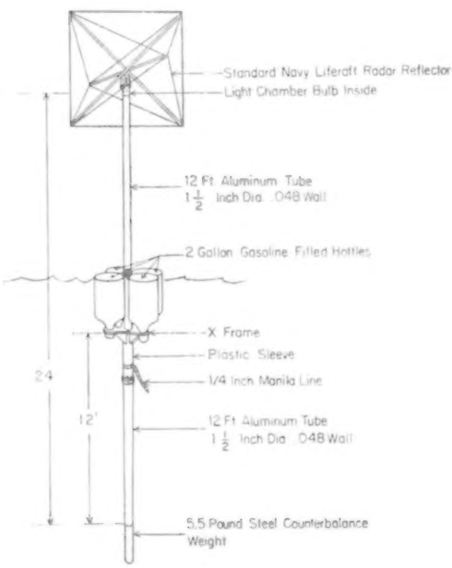


FIG. 1.



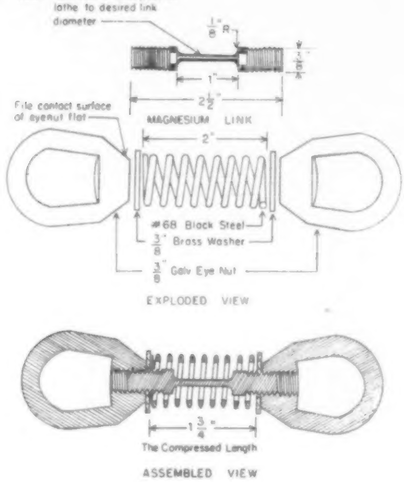
MARKER BUOY

FIG, 2.

The present system has been used to depths of 2,000 fathoms (although it is not limited to this), and has remained on the bottom for periods longer than ten hours, carrying as much as 25 pounds of payload.

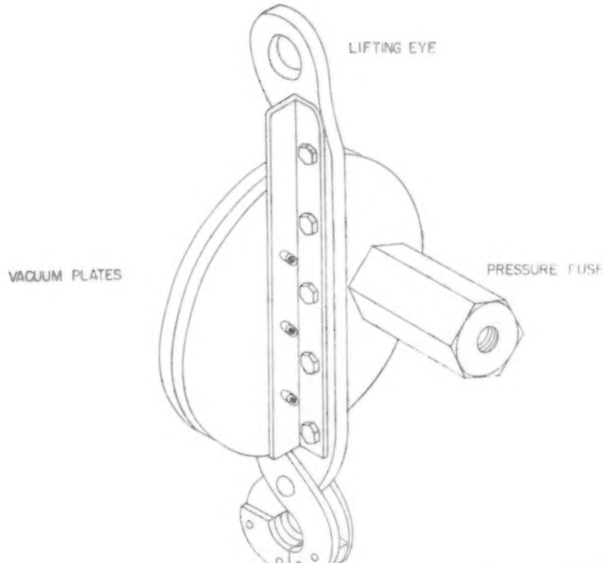
Table 1

No.	*Launching Date*	*Depth Fm.*	*Location (see map)*	*Launching time*	*Sighting time*	*Catch*
1	4/23/59	450	Test 1	11.30	14.30	6 sable fish – *Anoplopoma fimbria*; 6 hagfish – *Myxine circifrons*;
2	5/19/59	746	Test 2	11.00	15.41	3 sable fish; 3 hagfish; 1 lithodid crab; 1 Copepod; 1 octopus (partially digested)
3	6/21/59	650	Test 3	11.00	18.45	Over 50 hagfish (3 species); 5 sable fish; 1 brittlestar; 1 Pacific rattail – *Coryphaenoides acrolepis*
4	7/24/59	1107	Test 4	19.39	14.40	2 rosy snailfish – *Paraliparis rosaceus*; hagfish 5 eelpout – *Lycodes* sp. assorted small Amphipods. (Experimental model)
5	7/24/59	1107	Test 4	20.03	10.30	
6	9/9/59	1855	Test 5	11.40	not recovered	
7	9/9/59	1840		12.25	8.20	no specimens
8	9/9/59	1970	High seas difficult navigation	13.00	21.52	no specimens, trap damaged
9	9/9/59	2050		13.35	not recovered	
10	9/9/59	630	first large scale experiment	10.50	21.10	5 sable fish
11	9/9/59			11.40	not recovered	
12	9/9/59			11.10	not recovered	experimental model
13	10/27/59	950	Test 6	2.10	14.15	3 lithodid crabs; 3 hagfish; 1 rosy snailfish 1 Pacific rattail
14	10/27/59	945		2.20	15.00	3 crabs; 1 eelpout – *Lycodes* sp.; assorted Amphipods
15	10/28/59	1170		21.00	7.35	1 hagfish; 1 flatnose codling – *Antimora rostrata*; 5 eelpouts – *Lycodes* sp.
16	10/28/59	1170		21.15	8.36	2 hagfish (1 albino); 1 eelpout – *Lycodes* sp.
17	3/9/60	105	Test 7	1.15	6.30	1 *Sebastodes eos*
18	3/9/60	120		1.30	6.30	3 *Sebastodes eos* 1 " *macdonaldi*



MAGNESIUM TIME RELEASE

FIG. 3.



PRESSURE RELEASE MECHANISM

FIG. 4.

DEVELOPMENT

The DFV was designed for use on two different types of operations. Primarily the vehicles should supplement conventional oceanographic techniques. They should be suitable for quick launching and the ship should be allowed to proceed with other measurements until the vehicles resurface, with a minimum amount of time devoted both to launching and recovery. Secondly, the vehicle system should lend itself to mass deployment and large-scale sampling of the physical or biological characteristics of an area.

The type of instrumentation that the vehicle is intended to transport determines the necessary buoyancy and fixes the size and weight to a great extent.

Other factors considered in the preliminary design are: ease of handling, simplicity of fabrication and assembly, reliability of operation, and versatility.

Since ease of handling was important, the vehicle was designed to accommodate light instruments. The main buoyancy was separated from the marker buoy to reduce the size of the loads to be handled.

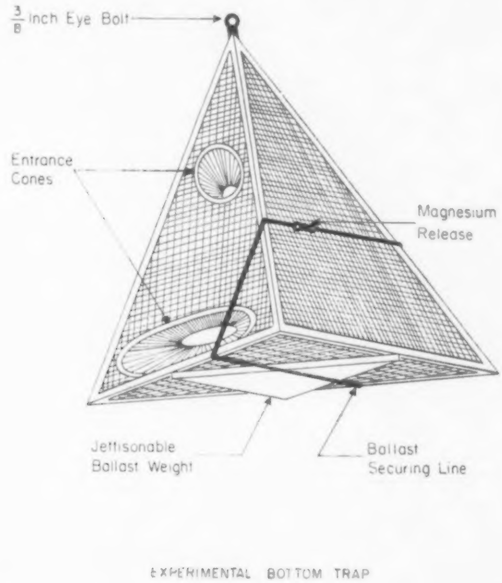


FIG. 5.

Buoyancy

Polyethylene carboys filled with gasoline are used to provide the main buoyancy of the system. These 13 gallon (nominal size) containers weigh 90 pounds in air when filled with regular gasoline, and provide 31 pounds of buoyancy in sea water. Flexible containers of this type are necessary to allow for the expansion and contraction of the gasoline with temperature and pressure changes. For light weight instruments, one carboy provides sufficient buoyancy. For heavier instruments two or more carboys can be tied to the line at intervals to provide the necessary buoyancy.

Marker Buoy

Four gasoline filled polyethylene bottles (two gallons each) provide the buoyancy of the marker buoy (Fig. 2). These are assembled in a cluster around the mast and clamped to an X-shaped plastic frame. The aluminium mast is made of two 12-foot sections of $1\frac{1}{2}$ in. tubing. Each of these is plugged into the plastic centre sleeve and secured with hose clamps. A standard life boat radar reflector is fitted to the top of the mast, and a six pound counter balance to the bottom. The reflector has provided radar contact to 4 miles.

Ballast Release

The DFV system can be provided with a time delay release, a pressure (depth) release, or a bottom contact release (Figs. 3 and 4).

Early tests were carried out with a magnesium time delay release. This device makes use of the electrochemical deterioration of a magnesium weak link in sea water. The release delay time can be predicted with reasonable accuracy, and can be adjusted for from 4 to 40 hours delay by varying the diameter of the magnesium link (VAN DORN, 1953). A clock actuated release is currently under development, which will extend the release time to a year or more.

The pressure release (Fig. 4) releases the ballast weight at a predetermined depth.

Instruments

The first sampling instrument developed for use with the free vehicle was a bottom fish trap (Fig. 5). This device consisted of a pyramid shaped aluminium frame, 6 ft on a side, covered with a plastic screen. The fish are retained in the trap by virtue of the maze effect provided by the design of the entrance cones. These traps are quite successful in capturing bottom and near bottom organisms, and have been launched on seven different cruises in widely scattered areas off the coast of

FIG. 6.

Southern California. The results of these launchings are tabulated below and in Fig. 6. The specimens are most often captured alive, but die soon after reaching the surface, due mainly to temperature changes. On one occasion, sable fish were kept alive for about 4 hours. It is believed that the use of equipment designed to maintain the proper temperature would enable many rare specimens to be preserved alive for further laboratory study.

A larger folding version of the bottom trap is presently under development, which is designed to prevent any possible escape of the trapped creatures, and to retain a sample of cold bottom water to help preserve specimens alive until transferred.

Other instruments under development or test for use with the free vehicle include: a recording deep current meter, sedimentation measuring and collecting devices, water and gas sampling gear, and multiple short coring tubes.

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LETTER TO THE EDITORS

Observations of irregular motion in the open ocean

(*Received* 29 *February* 1960)

It is believed that the following observations are examples of turbulent motion in the open ocean at depths well below the wind stirred layer. The depth of the mixed layer in the area where these measurements were made is 50–100 metres. Observations with neutral buoyant current floats have often indicated irregular movement (Swallow, 1955, 1957); but since these observations have always been made with reference to anchored buoys, it has usually been impossible to determine how much of this erratic movement is real and how much is an artifact resulting from the swinging of the buoy on its anchor.

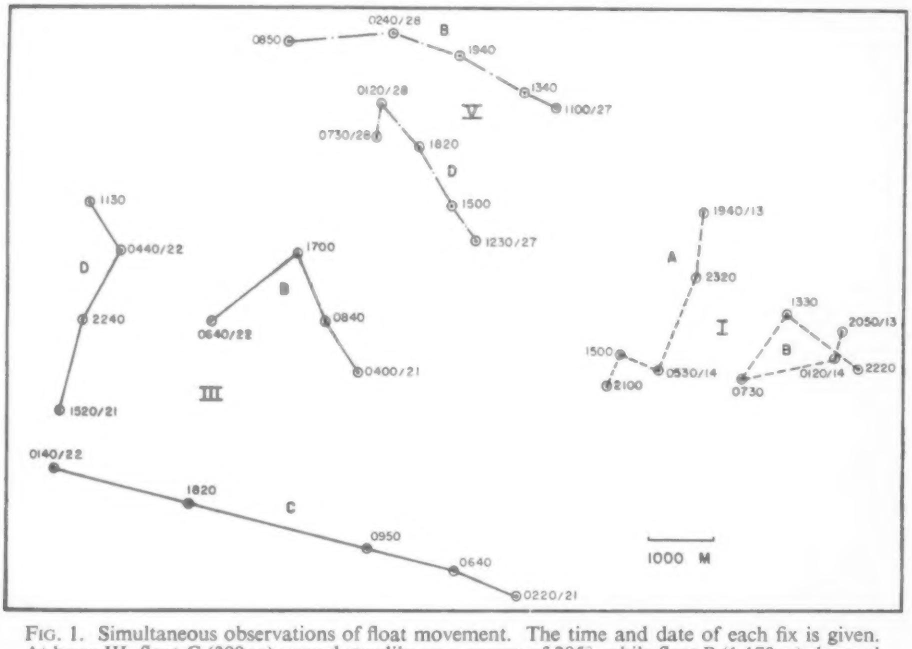

Fig. 1. Simultaneous observations of float movement. The time and date of each fix is given. At buoy III, float C (300 m) moved steadily on a course of 285°, while float B (1,170 m) changed course some 90° and float D (1,720 m) changed about 45°. At buoy V, float B (1,070 m) moved in a slightly curving path toward the west while float D (810 m) turned almost completely back upon itself. At buoy I, both floats A (720 m) and B (2,140 m) executed irregular movement, apparently independent of one another.

On a recent cruise it was possible on several occasions to follow two or more floats simultaneously. Under these circumstances if one float moves steadily and the other irregularly, or if both should move irregularly but differently from one another, it is difficult to assign any explanation to this movement, other than that such erratic motion is real.

Three examples of such motion are given (the pertinent data on the floats in Table 1, that portion of the tracks which best show the turbulent motion in Fig. 1). All positions are based on three bearing fixes. The accuracy of the individual fixes is about 200 metres. All measurements were made

Table 1.

Position *N*	*W*	*Date*	*Float Number*	*Depth*	*Hrs. Tracked*	*Mean Velocity (cm/sec)*	*(toward)*
15° 08′	120° 02′	12 July	I–A	720 ± 270	57	2·5 ± 0·2	183° ± 0°
		13 July	I–D	2140 ± 440	38	1·2 ± 0·3	150° ± 17°
7° 30′	120° 00′	20 July	III–B	1170 ± 310	49	4·3 ± 0·3	300° ± 4°
		20 July	III–C	500 ± 230	40	6·6 ± 0·3	270° ± 3°
		21 July	III–D	1720 ± 300	31	4·7 ± 0·4	004° ± 5°
5° 32′	120° 05′	26 July	V–B	1070 ± 270	43	5·3 ± 0·3	268° ± 3°
		27 July	V–D	810 ± 220	19	3·4 ± 0·7	314° ± 12°

Data on seven neutrally-buoyant floats tracked on the DORADO Expedition, July-August, 1959.

with reference to a taut wire mooring whose radius of swing is about 350 metres (KNAUSS, 1960). It is believed that these observations are examples of turbulence (or possibly, internal waves). If the motion were either barotropic or tidal, then the non-steady portion of the movement should be the same for all floats independent of depth.

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SWALLOW J. C. (1955) A neutral buoyancy float for measuring deep currents. *Deep-Sea Res.* **3**, 74-81.
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BOOK REVIEW

The Sea off Southern California (A modern habitat of petroleum). K. O. Emery. John Wiley and Sons, New York, Chapman and Hall, London. 366 pages, price $12·50.

The publication of this volume by Emery is a major event in the rapidly expanding science of marine geology. The author's name, or the subtitle, more than the title, prepares the reader for a book with emphasis on a geological approach to problems of the sea. No other publication dealing with a limited part of the oceans covers so wide a variety of aspects. Moreover, each subject is treated in considerable detail. Few will have realised just how vast the store of data concerning this area already is and how far the interpretation has advanced. To have brought together and co-ordinated all this information and presented it authoritatively, yet in a manner that is both pleasing to the eye and to the scientific mind, is an achievement for which not only marine geologists and all oceanographers will be thankful, but also all geologists interested in sediments and structure. One already knows the author as a man of great energy and versatility, full of original ideas and yet with sound methods of research. He now shows himself a lucid compiler as well. He has been concerned directly or indirectly with most of the problems involved and he is responsible for a significant part of what has been attained as either author, co-author or research sponsor.

Two aspects of this volume deserve special mention. One is that Emery, a careful and sober guide through the maze of data and interpretations, is not particularly concerned with hypothetical speculations. His unbiased treatment of the origin of submarine canyons is an example of the art of how to sit on a fence in spite of being actively engaged in the field it crosses. The other noteworthy aspect is that Emery has remained in contact with general geology, more especially oil geology, so that he keeps in mind what his terrestrial colleagues will want to know and which form of presentation will be useful to them. The sub-title ' A modern habitat of petroleum ' is therefore a slogan very much to the point.

The chapters cover: *Physiography* from the coast and its run-off, with the beaches and their sea caves to the abyssal sea floor. *Lithology* dealing with rock bottom and authigenic phosphorite. *Structure* as revealed by topography, seismicity, geomagnetism and gravity. *Water* under the subheadings: currents, waves, tides. *Life* as it appears in various environments, and the organic budget. *Sediments*, by far the largest chapter, first describes the deposits by environment, including a treatment of glauconite, then considers sources, transportation and deposition (also rate of accumulation), interstitial water, organic matter and the origin of petroleum. *Economic aspects* forms the closing chapter and covers such matters as pollution, fisheries, landslides, bathing beaches, mineral recovery. A full index and bibilography are useful assets.

It cost the reviewer some trouble to find the traditional corrections as evidence that he has read beyond the cover. Coriolis lost an s in producing his force on p.100 and San Clemente Island was elevated to tower far above the 2,000 ft altitude at which the view of Fig. 67 was taken. The 248 illustrations and deep-sea chart are major sources of data (Fig. 33 would have been excellent if it had been reproduced better). The drawings are of exceptional quality and many reflect the ingenuity of the author in presenting information graphically in a highly convenient manner.

Submarine geology as a whole-time occupation is a creation of Shepard's and it is fitting that one of his pupils is the man to produce this superb compilation for the classical area. The dedication is also to Captain Hancock, the sponsor of Emery's own research.

Ph. H. Kuenen

NOTICE

Tenth Pacific Science Congress

Preliminary Announcement

The Tenth Pacific Science Congress of the Pacific Science Association will be held at the University of Hawaii, Honolulu, from 21 August to 6 September 1961, sponsored by the National Academy of Sciences, Washington, D.C., and Bernice P. Bishop Museum, with the cooperation of the University of Hawaii. Scientific sessions will be held from 21 August to 2 September, with a post-sessional field trip through 6 September.

PACIFIC SCIENCE ASSOCIATION

The Pacific Science Association is an international, regional, non-governmental scientific organization, founded in 1920 by the holding of the First Pan-Pacific Scientific Conference in Honolulu. The Association's permanent headquarters is at the Bishop Museum, Honolulu 17, Hawaii, U.S.A. Previous Congresses :

1920, Honolulu, Hawaii; 1923, Melbourne and Sydney, Australia; 1926, Tokyo, Japan; 1929, Batavia and Bandoeng, Java; 1933, Victoria and Vancouver, Canada; 1939, Berkeley, Stanford and San Francisco, U.S.A.; 1949, Auckland and Christchurch, New Zealand; 1953, Quezon City, Phillipines; 1957, Bangkok, Thailand.

TENTH PACIFIC SCIENCE CONGRESS

Each Pacific Science Congress is held under the auspices of the organization which represents the Pacific Science Association in the host country. At its meetings during the Ninth Congress, the Council of the Association accepted the joint invitation of the National Academy of Sciences and Bernice P. Bishop Museum for the Tenth Congress to meet in Hawaii in 1961. This invitation was offered with the full cooperation of the University of Hawaii, on the campus of which the meetings will be held. Officers of the Congress and programme organizers are appointed by the organizations under whose auspices the Congress is held, and the administrative expenses of the Congress are defrayed by these organizations.

Officers, Tenth Congress

Honorary President, Detlev W. Bronk, President, National Academy of Sciences. President, Laurence H. Snyder, President, The University of Hawaii. Honorary Vice-Presidents, A. P. Elkin. The University of Sydney, Australia. Koji Hidaka, Tokyo University, Japan. C. E. Pemberton, Hawaiian Sugar Planters' Association Experiment Station, Hawaii. Knowles A. Ryerson, University of California, U.S.A. Air Marshal Muni M. Vejyant-Rangsrisht, Chulalongkorn University, Thailand.

Secretary General, Harold J. Coolidge, Executive Director, Pacific Science Board, National Academy of Sciences.

Members of the Executive Committee

L. H. Snyder, H. J. Coolidge, Robert W. Hiatt, Knowles A. Ryerson, G. P. Murdock, Alexander Spoehr, C. E. Pemberton, Harry Wexler.

PROGRAMME

The programme is being organized under Sections and Divisions. Symposia are the main divisional meetings, but provision is also being made for sessions of grouped papers and sessions of contributed papers. In addition to sectional and divisional programmes there will be a limited number of special symposia of broad general interest.

I. Section of Geophysical Sciences
- A. Division of Meteorology and Upper Atmosphere.
- B. Division of Oceanography.
- C. Division of Solid Earth Sciences.

II. Section of Biological Sciences
- A. Division of Zoology and Entomology.
- B. Division of Marine Biology and Fisheries.
- C. Division of Limnology and Fresh-water Fisheries.
- D. Division of Botany.

III. Section of Public Health and Medical Sciences
- A. Division of Public Health and Medical Sciences.
- B. Division of Nutrition.

IV. Section of Agricultural Sciences
- A. Division of Animal Science.
- B. Division of Crop Science.
- C. Division of Soil Science.

V. Section of Forestry
- A. Division of Forest Biology
- B. Division of Forest Management
- C. Division of Forest Products

VI. Section of Conservation

VII. Section of Anthropology and Social Sciences

VIII. Section of Geography
- A. Division of Cartography
- B. Division of Physical Geography.
- C. Division of Human Geography.
- D. Division of Regional Geography : The Pacific Islands.

IX. Section of Scientific Information

Public Lectures and Panel Discussions

In addition to the regular daily scientific sessions, there will be a programme of public lectures and evening panel discussions.

Exhibits

A display of exhibits will be arranged, including an exhibit on Pacific publications to include examples of the work of the major presses publishing works on Pacific science.

Travel and Hotel Accommodation

Scientists attending the Congress must make their own arrangements for travel and hotel accommodation. The American Express Company is designated the principal travel agent for the Congress, and its offices throughout the world will assist scientists who plan to attend.

Dormitory Accommodation

A limited amount of dormitory accommodation will be available at the University of Hawaii and possibly at other educational institutions in Honolulu. For this inexpensive accommodation scientists from countries other than the United States will be given preference. Applications for dormitory accommodation should be sent to : The Chairman, Accommodation Committee, Tenth Pacific Science Congress, Bishop Museum, Honolulu 17, Hawaii.

Field Trips

During the two weeks of meetings a programme of field trips on Oahu (the island on which Honolulu is situated) will be arranged for scientists to see institutions and other places of interest to particular disciplines.

Following the closing plenary session of Saturday, 2 September, post-sessional field trips will give an opportunity to see other islands of the Hawaiian chain. Principal centre for these tours will be the island of Hawaii, where the volcano Kilauea is situated.

Countries, Dominions, Colonies and Territories, eligible for membership in the Association, whose scientists have participated in previous Congresses

American Samoa, Argentina, Australia, Cambodia, Canada, Chile, China (Taiwan), Colombia, Costa Rica, Ecuador, El Salvador, Fiji, France, French Establishments in Oceania, Guam, Guatemala, Hawaii, Honduras, Hong Kong, Indonesia, Japan, Korea (South), Laos, Macao, Malaya, Mexico, Netherlands, Netherlands New Guinea, New Caledonia and Dependencies, New Zealand, Nicaragua,

North Borneo, Panama, Peru, Philippines, Portugal, Portugese Timor, Ryukyu Islands, Sarawak, Singapore, Thailand, Tonga, Union of Soviet Socialist Republics, United Kingdom of Great Britain and Northern Ireland, United States of America, U.S. Trust Territory of the Pacific Islands, Viet-Nam (South). Western Pacific High Commission Territories, Western Samoa.

In addition, the following non-member countries of the Pacific Science Association have received invitations to participate :

BOLIVIA BURMA DENMARK NORWAY SWEDEN.

Circular of Information

The Congress Circular of Information, with more detail on programme, field trips, and other matters, will be issued in August, 1960.

Please address enquiries to: Secretary-General, Tenth Pacific Science Congress, Bishop Museum, Honolulu 17, Hawaii, U.S.A. From this address the enquiry will be forwarded to the person concerned.

An interplain deep-sea channel system

A. S. LAUGHTON

(*Received* 14 *January* 1960)

Abstract—A system of channels connecting the Biscay and Iberia plains was discovered in 1958. Two main channels cut through the sill and join after 20 miles. The total length between plains is 50 miles and the width of the channels varies from 2 to 10 miles. The change of level between plains occurs where the channel first leaves the upper plain. The channel shows a meander formation similar to a subaerial river. Cores show that turbidity currents have been active in the past. Small feeding channels on the Biscay plain converge on the interplain channels.

It is concluded that turbidity currents initiated on the continental shelves and flowing across the Biscay plain can be rejuvenated by the increase in gradient and lateral constriction, and flow through to the Iberia plain where they finally deposit their load.

INTRODUCTION

AN EXAMINATION of the bathymetric charts covering the Biscay and Iberia abyssal plains showed that, although they are separated by only 40 miles, there is a difference of level between them of 100 fm (Fig. 1 and 2). This suggested that the Biscay plain,

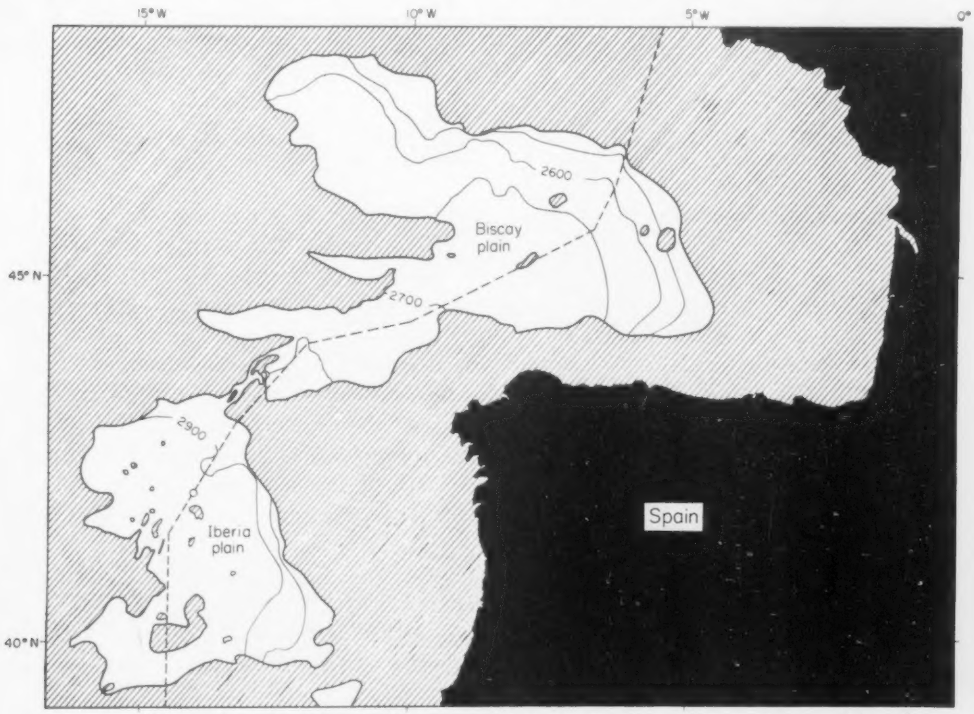

FIG. 1. Biscay and Iberia abyssal plains. Depths in fathoms (corrected). Contour interval on plain – 50 fm. Stippled area – sea bed that is not abyssal plain
- - - - - - - - location of profile in Fig. 2.

being the higher, was confined by a sill separating it from the Iberia plain. However, the narrowness of this sill and its small height above the Biscay plain led the author to investigate the possibility of some connection between the two plains. A preliminary line of soundings taken in 1956 showed that the sill was, in at least one place, as narrow as 4 miles and this led to a thorough investigation being made in 1958. This survey showed a system of channels connecting the two plains and it was found that the 1956 line of soundings had been made, for the most part, along the axis of the main channel.

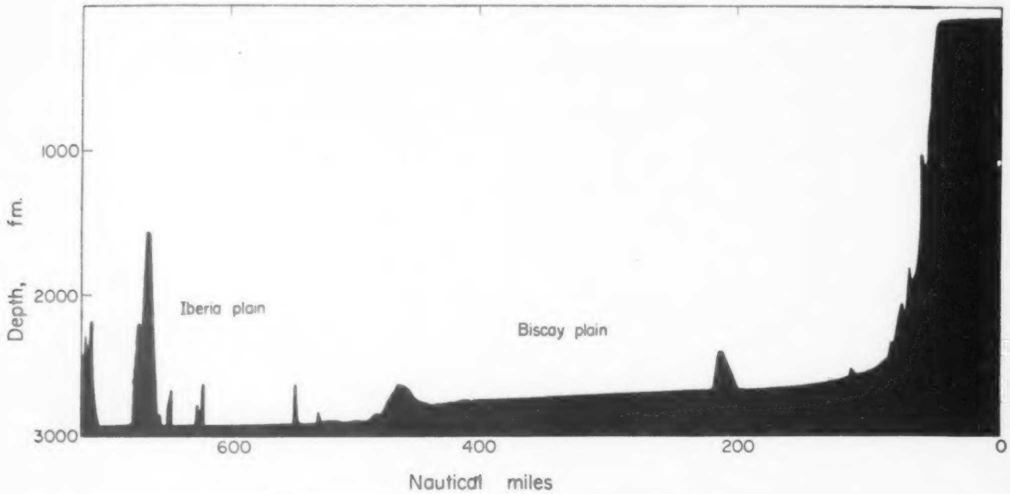

FIG. 2. Profile of Biscay and Iberia abyssal plains showing difference of levels. Depth in fathoms (corrected). Vertical exaggeration – approx. 110 : 1.

This connection between the Biscay and Iberia plains has been described briefly by HEEZEN *et al.*, (1959) and has been called by him the Theta gap. Heezen defines an abyssal gap as 'a constricted passage connecting two abyssal plains which, in the vicinity of the gap, lie at different levels' (p. 66), and he notes that they are connected with 'mid-ocean canyons' on the higher abyssal plain, which lead to the gap. Other workers (DILL *et al.*, 1954, MENARD, 1955, DIETZ, 1958) have used the name 'deep-sea channel' to describe features of the mid-ocean canyon type to distinguish them from the submarine canyons of the continental shelf from which they differ in many respects. It is therefore proposed that the features described in the first part of this paper should be called interplain deep-sea channels to emphasise their continuity with those on the abyssal plain, and to underline their general form which is associated with horizontal flow.

SURVEY

A survey was made by R.R.S. *Discovery II*, 21–25 July 1958 (Fig. 3). An approach run to the area crossed the main channel four times before a buoy carrying a radar target was laid on the sill. This was laid in 2600 fm at a position 43° 37′N, 12° 43′W and its scope allowed it a movement of about 1 mile. The survey was conducted using radar fixes on the buoy up to a range of about seven miles and beyond this

using dead reckoning runs suitably corrected by extrapolation of conditions within the radar range. Some of the tracks were adjusted to give correct cross-over values depth and magnetic field. Additional lines of soundings from previous cruises have been used to fill in the broad outlines of the regional topography.

Most of the soundings were made with the N.I.O. precision echo-sounder in which the time base is controlled with an accuracy of 1 part in 10^5. The nominal depth (based on an assumed velocity of sound in sea water of 800 fms/sec.) can therefore be measured with an accuracy of 1 fm. The soundings given in the charts and figures

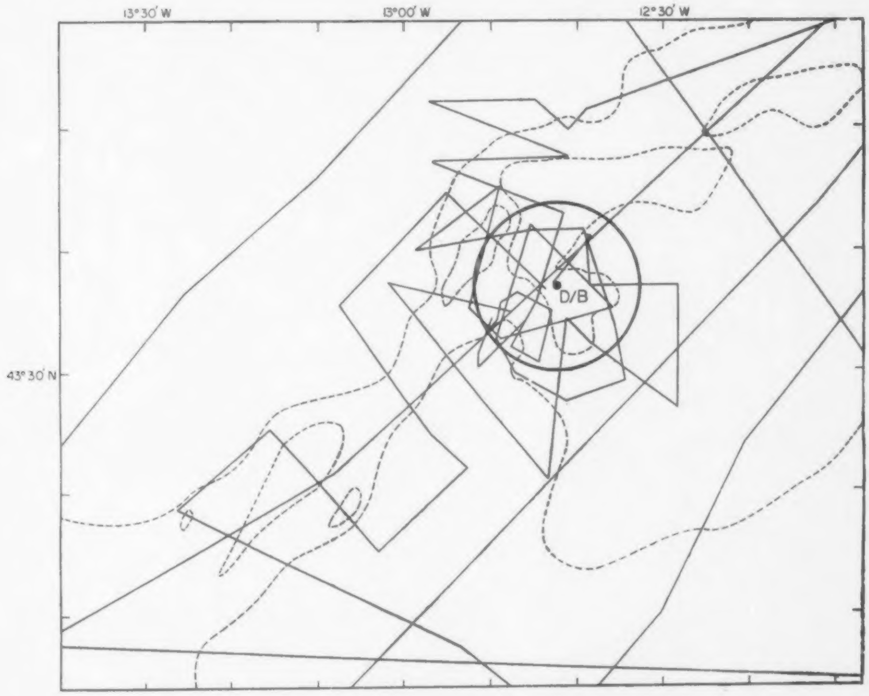

FIG. 3. Track chart of interplain channel survey

are uncorrected for the depth of the transducer (4 fm) or for variations in the velocity of sound in sea water. Older soundings, taken with a Kelvin Hughes MS 26 E echo-sounder have been adjusted on the same basis.

(1) *Description of the interplain channels*

The results of the topographic survey are shown in Fig. 4.* Two channels lead out of the south-west corner of the Biscay abyssal plain. After 20 miles they join to form a broader channel which divides around a ' middle ground ' before leading into the Iberia plain. The total length along the axes of greatest depth is 55 miles via the northern channel and 50 miles via the southern channel. The width varies from 2 to 10 miles, being fairly narrow at the upper end and broader at the lower end. It is not in general possible to give a depth of the channel since it is confined

*The diagrams have been amended following further survey work carried out in March, 1960.

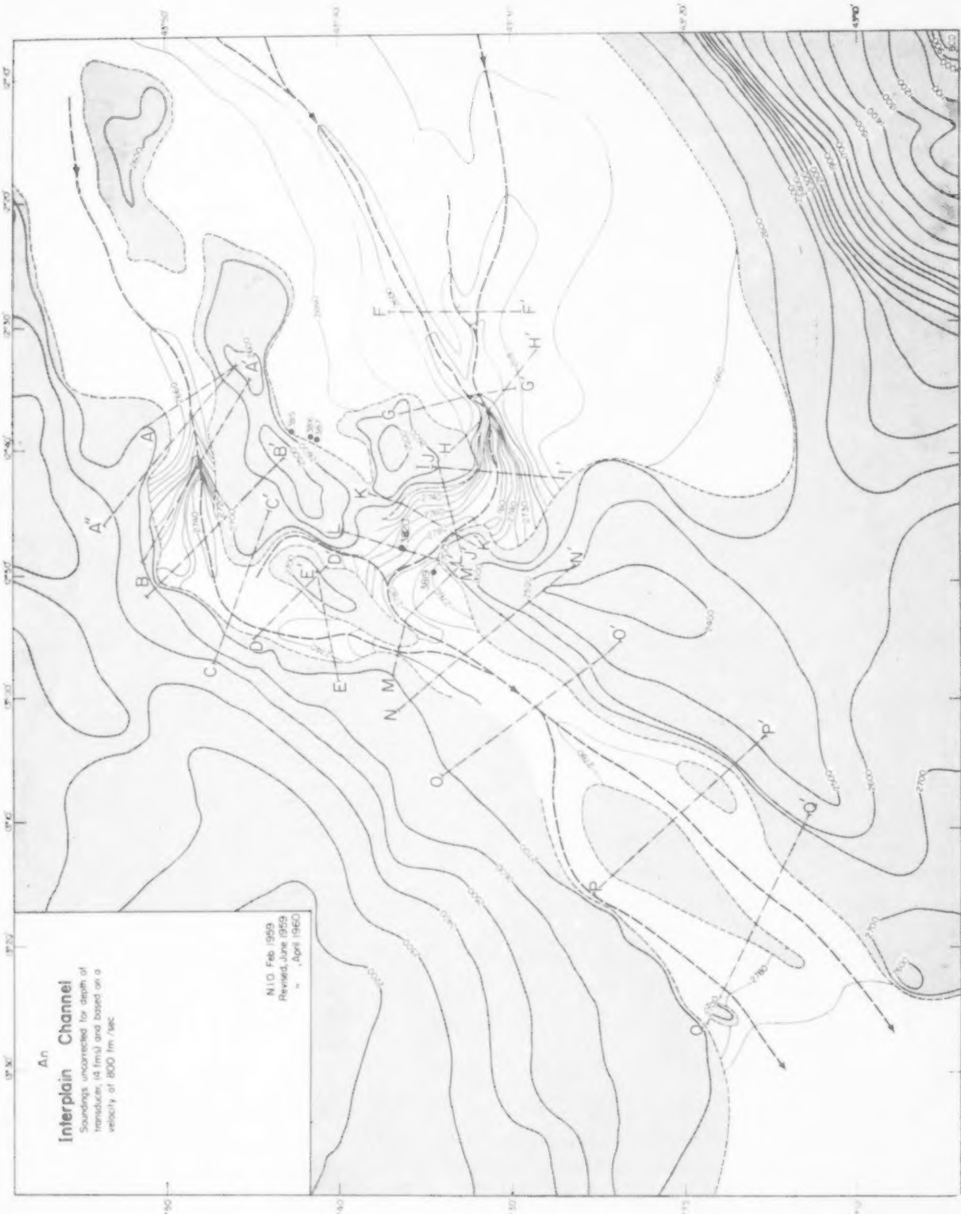

FIG. 4. Contour chart of interplain system. Depths in fm (uncorrected). Stippled area – hilly area with 100 fm contour interval. Unstippled area – abyssal plain and channel system with 5 fm contour interval.
--->--- axes of channels A------A′ profiles illustrated in Figure 5 ● position of core stations.

between seamounts rising several hundreds of fm above the general level of the plains. However, where the southern channel first leaves the Biscay plain it cuts 85 fm below the level of the plain (cf. Profile HH′ Fig. 5).

The course of the channels was probably initially dictated by the position of the local hills of hard rock (cf. magnetic data discussed later). The southern channel appears first as a deep rough bottomed depression in the Biscay plain following the confluence of three feeding channels on the plain. These feeding channels will be discussed later. The rough bottom of the channel in profile HH′ and its position relative to the hills comprising the sill suggest that it is an erosional feature and has been cut back progressively into the plain. Once the channel enters the sill region

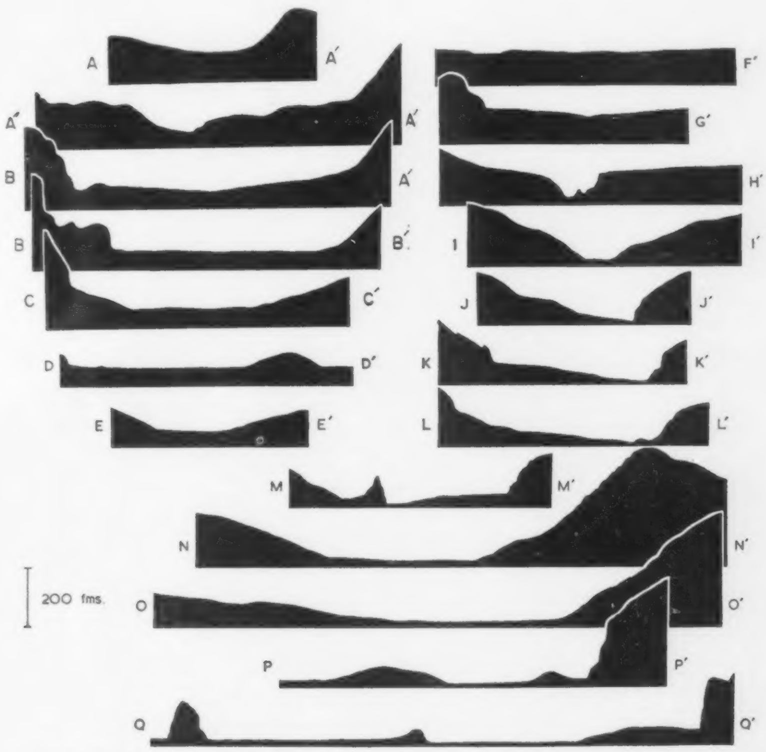

FIG. 5. Profiles of interplain channels. Vertical exaggeration – 8·4 : 1.

it becomes flat bottomed. As the channel curves, the deepest point is found on the outside of the curve, the smooth floor being always inclined away from the centre of curvature. The S-shaped course of the channel and the distribution of depths is very similar to a meander in a subaerial river. The steepness of the banks on the outside of the bends and their character on the echo-sounding record suggest that erosion and subsequent slumping has taken place.

A tributary, possibly a branch of the northern channel, joins the southern channel after 15 miles. The main branch of the northern channel joins 5 miles further on.

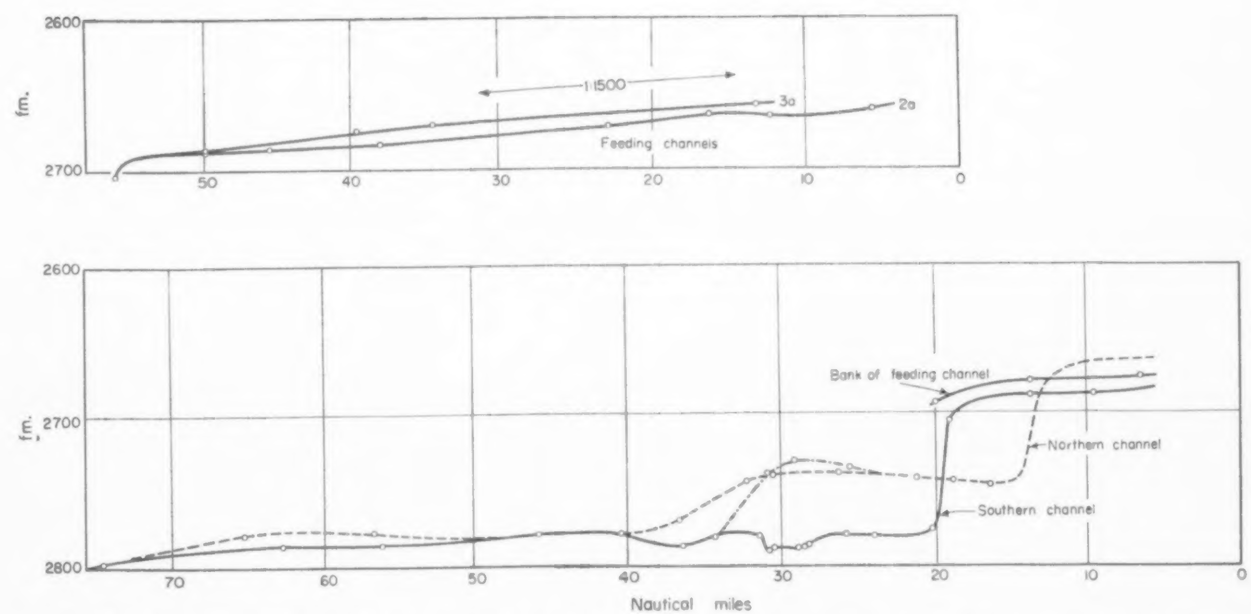

FIG. 6. Axial profile of feeding and interplain channels. Depth in fm (uncorrected). Vertical exaggeration – 100 : 1.

The northern channel has not been as fully surveyed as the southern channel. In general it is broader and flatter than the southern channel and 40 fm shallower, but it has constrictions at either end (cf. sections A to E and M, Fig. 5). The steep initial cut shown on the contoured chart has not been surveyed and is postulated on the basis of similarity with the southern channel.

The channel, after the northern and southern branches have joined, is broader and somewhat shallower than the deepest part of the southern channel. When it divides again around a central rise, the depth of the north-west branch is 9 fm less than the south-east branch. After emergence into the Iberia plain, there are no indications of discrete channels.

A longitudinal profile of the interplain channels is shown in Fig. 6, based on the deepest points of sections across the channels. The most important feature is the sudden drop of 71 fm between sections G and H separated by 1 mile. Assuming a constant gradient between them the gradient is 1 in 14. This, however, is a minimum value and it is quite possible that it is much greater. The two deep points 10 and 16 miles downstream are associated with the tilt of the bed in the meander. The remainder of the channel grades gently and smoothly into the Iberia plain at 1 in 2000. The features of the longitudinal profile suggest that the only region of active vertical erosion is in the vicinity of the upper end of the channel. In the meander, erosion of the banks has taken place and a balance between erosion and deposition has resulted in the inclined channel bed. In the lower half, deposition appears to predominate.

(2) *Feeding channels*

Section F in Fig. 5 shows the existence of three shallow channels on the Biscay plain leading to the southern interplain channel. An examination of all available sounding profiles on the south-west section of the Biscay plain revealed a coherent system of channels lying in a broad shallow depression on the plain (Fig. 7). All of the sounding profiles had been taken by R.R.S. *Discovery II*, the older ones on the Kelvin Hughes echo-sounder and the more recent on the N.I.O. precision echo-sounder. It is interesting to note that in all cases on the plain, the soundings taken by the Kelvin Hughes sounder, after correction for speed variations of the stylus which were measured every half-hour, agreed with the precision soundings within $\pm$ 2 fm.

The soundings enabled the region to be contoured at 5 fm intervals with few areas of ambiguity. In one or two cases the position of the tracks had to be adjusted in order to remove anomalies of contouring. Contouring between sounding lines was based on the topographic trends revealed by the profiles, such as to give the simplest picture. Where there was some ambiguity regarding which channel sections should be connected, it was assumed that there was a continuous downhill gradient of the channel bed. This assumption seems to be justified by the smoothness of the longitudinal profiles shown in Fig. 6.

The south-west leg of the Biscay abyssal plain shows a more or less steady gradient in a west-south-west direction of about 1 in 2500, until it reaches 11°W, when the pattern of feeding channels begins to appear and the abyssal plain flatness is interrupted. Another branch of the plain 25 miles wide by 80 miles long, joins this region from the west with a gradient of 1 in 2000 to the east.

Associated with the channels is a broad depression, 20 or 30 fm deep, extending


Feeding Channels in the Southwest Biscay abyssal plain
Soundings not corrected for depth of transducer, (4 fm.) and based on a velocity of 800 fm./sec
Contour interval 5 fm on the plain above 2700 fm.
Legend
Axes of channels
Sounding lines
Hilly areas
Northern Channel
Southern Channel

FIG. 7.

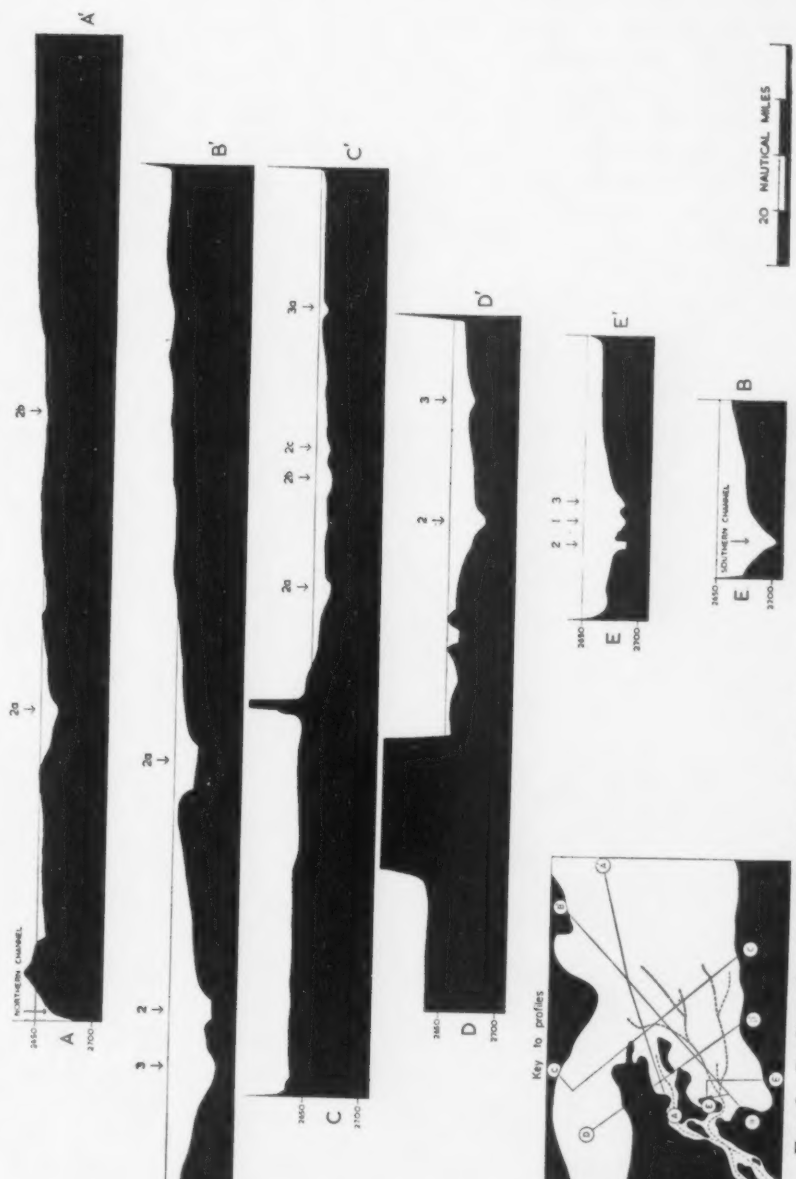

FIG. 8. Profiles of south-west Biscay abyssal plain. Depth in fm (uncorrected). Vertical exaggeration – 100 : 1.

across the S.W. leg of the Biscay plain and covering an area of 2500 square miles. The feeding channels show a dendritic pattern, six channels joining to give two and again to give one deep channel leading into the southern interplain channel. Sections of the channels themselves show variations from flat bottom to V-shaped (Fig. 8).

The principle channel located in the centre of the depression (2a–2) is about 50 miles long and shows a remarkably constant gradient of 1 in 1500, until it enters the southern interplain channel. It varies in shape throughout its length. On section AA′ it has a rounded section, on CC′ it is nearly flat bottomed, on BB′ it is flat bottomed at both crossings, on DD′ it is V-shaped and on EE′ is again flat bottomed. The flat bottomed sections show the bottom to be sloping across the channel down to the east, about 10 fm below the level of the banks. Channel 2a is joined by 2b which may extend for 50 miles above the junction although it does not have such a clear cut channel form. Rather, it is the axis of the deepest part of a shallow valley.

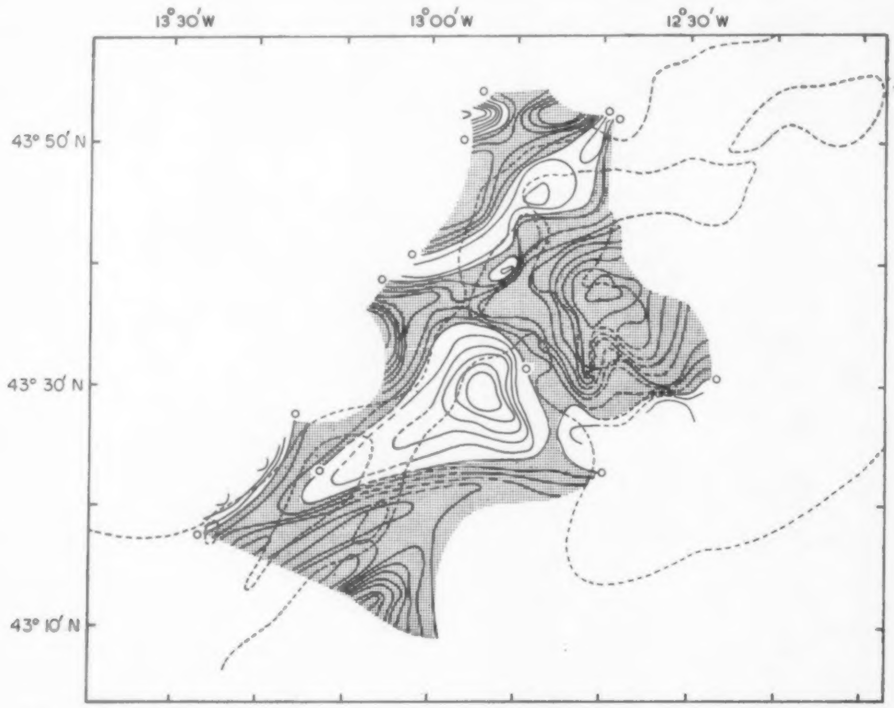

Fig. 9. Chart of anomalies of the total intensity of the earth's magnetic field (corrected for diurnal variation and the regional trend removed). Contour interval – 20 gamma (uncertain contours shown in dashed lines). Positive anomaly – stippled.

To the south, channel 3 is V-shaped throughout and lies on the side of the drainage depression. It extends for at least 40 miles with a gradient of 1 in 1500. It is joined near its lower end by a very small channel labelled (1).

What appears to be a channel with leveed banks in the centre of section DD′ has been shown by subsequent surveying to be a section of two hills south of the approaches to the northern channel.

No well defined channel leads into the northern interplain channel, although one can trace the axis of greatest depth in the branch of the plain leading to it. However this is higher than the channel 2a which bounds it on the eastern side suggesting that the more recent activity has been in the southern channel.

(3) *Magnetic field*

Throughout the topographic survey of the interplain channels, measurements were made of the total intensity of the earth's magnetic field using a proton spin magnetometer (Hill, 1959). The field data was corrected for diurnal variation and the regional trend was removed. The resulting map of magnetic anomalies is shown in Fig. 9.

Although there are no very large anomalies there is a reasonable correlation between the position of the anomalies and the coarse features of the topography. The northern channel correlates with a trough of negative anomaly, as does in a less certain way the main channel below the junction. The positive anomaly at 43° 37′N, 12° 40′W covers the high ground dividing the northern and southern

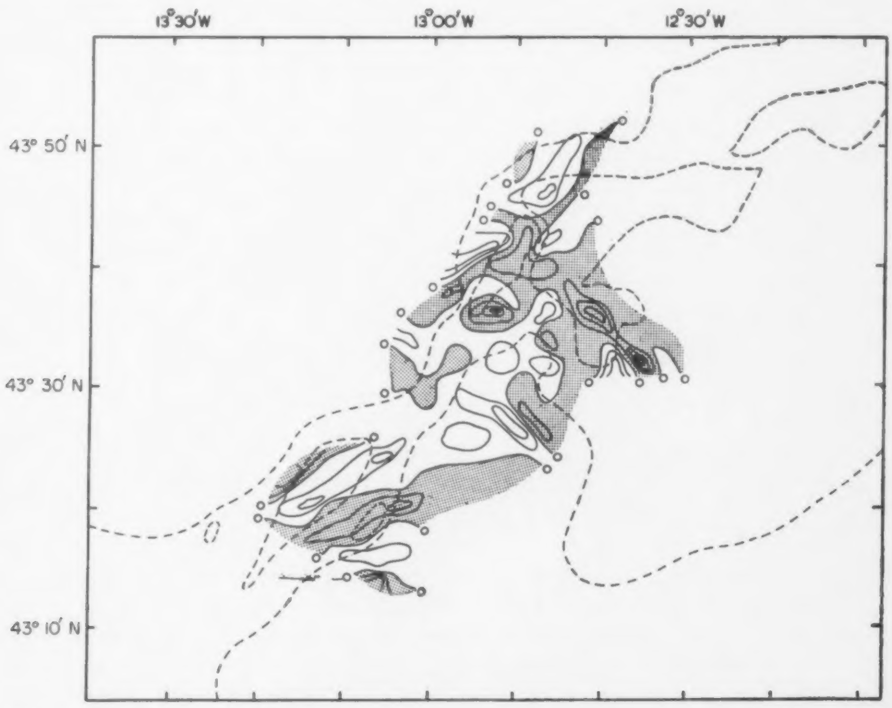

Fig. 10. Chart of curvature of the total intensity anomalies. Contour interval – 20 gamma per mile per mile. Positive values – stippled.

channels. In the absence of one clear-cut isolated anomaly, it is difficult to interpret the magnetic field in terms of the rock structure beneath the sediments. Following the technique of Vacquier *et al.*, (1951), a map of the curvature of the magnetic field was plotted. A curvature map has the property of revealing more clearly the

outlines of the magnetised bodies giving rise to the anomalies. The contour of zero curvature bordered by high positive curvature on one side and high negative curvature on the other lie over the discontinuities of magnetic properties. The sharper the discontinuity, the higher the curvatures.

The curvature plot of the magnetic field is shown in Fig. 10. Although it is not possible to identify unambiguously the blocks of magnetic material, the trends of the boundaries are more clearly revealed, and can be seen to correspond more or less with the axes of the three branches of the channel system. An estimate of the depth of the source of the anomalies from the ratio of their maximum steepness to maximum intensity shows that it lies close below the surface of the sediments.

The magnetic data suggest, therefore, that the basic Y-form of the channel system is a feature of the underlying hard rock structure and not the result purely of sedimentary processes. The rocks formed a sill limiting the south-west end of the Biscay plain and when the level of the plain came to exceed the minimum sill height, a path was found for the sediments to be transported down to the Iberia plain level. Subsequent sedimentation has covered up much of the rock structure but the channels remain.

(4) *Core samples*

Five cores were taken in the region with a piston corer. The trigger weight was also fitted with a short coring tube. Three of the cores were taken on the extreme edge of the abyssal plain between the channels, and the other two in the southern channel (Fig. 4). Sections of the cores are shown in Fig. 11. The three core stations on the plain, (3815, 3816 and 3817) yielded both main cores and trigger weight cores. Only the trigger weight cores and the short main core of 3817 have been studied at this time. The disturbance of the cores and the loss of the top section of 3816 is due to the fact that sediment was forced up beyond the coring tube. All three cores, taken within a mile of each other, show similar stratification. The top consists of pale brown globigerina ooze grading downwards to a strongly banded dark grey-brown clay, ending abruptly 20 cm below the surface. Within the gradation, there are signs of burrowing activity where the lighter ooze has been carried down into the darker clay. The sharp bottom boundary of the clay and the dark banding indicate a succession of turdibity current deposits. In core 3815 this pattern is repeated between 30 and 38 cm. Core 3817 shows patches of silt between 30 and 45 cm.

At core stations 3819 and 3820 in the southern channel, no main core was retained. On the jaws were traces of hard packed sand. The trigger weight cores lost the top few centimetres owing to excess penetration. They both consist chiefly of a mixture of grey clay and globigerina ooze and show several sharp boundaries where darker clay overlays lighter ooze. Above the boundaries, the colour fades gradually and there are signs of burrowing activity. Of most significance, there are patches and in places beds, of fine and medium quartz sands. It is reasonable to suppose that the failure to retain any sediment in the main coring tube implies that below the top half metre there is a considerably greater proportion of sand and silt. Past experience has shown that the core catcher used fails to retain sand and silt unless it lies above a plug of more coherent sediment.

Apart from abundant quartz, the sand contains mica, small quantities of quartzo-felspathic rocks, and some shell debris (mostly foraminiferal but including at least

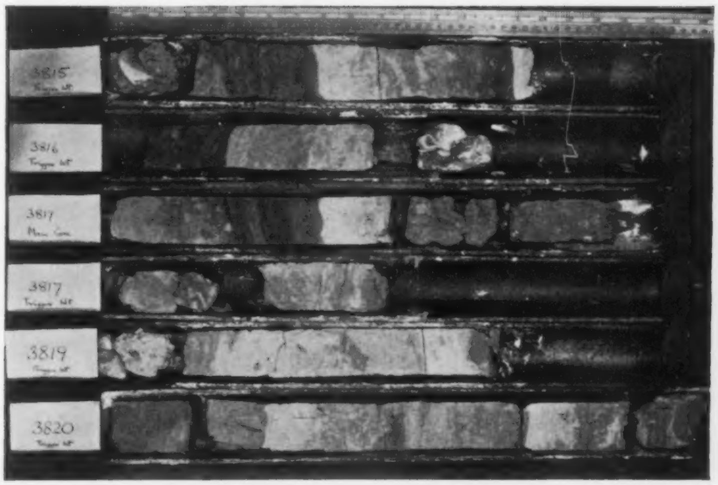

FIG. 11. Sections of cores from edge of Biscay plain and from centre of southern channel. The tops of the cores are on the left. Maximum length of core shown is 56 cm.

one piece of abraded brachiopod shell). All the larger grains were exceedingly well rounded.

The stratification in all cores shows the characteristics of turbidity current deposits interbedded with normal pelagic sediments. Core 3817, which best represents the top 30 cm of the sediment column, shows that turbidity currents have not been active near the edge of the plain in recent time. If a rate of sedimentation of globigerina ooze of 1 cm per 1000 years is assumed then the close of the last period of turbidity current activity is about 10,000 years ago, corresponding to the close of the last glacial period (Broecker, Turekian and Heezen, 1958). In the channel, it is possible that turbidity currents have been active more recently although direct evidence of this is not available. A more extensive coring programme is planned to provide fuller data on the sediments of the interplain channel system and the feeding channels.

DISCUSSION

The terrigenous sediments filling the Biscay plain are derived from the continental shelves surrounding the Bay of Biscay. The main contribution is from the shelf off the western approaches to the English Channel and off the coast of France, where a number of large rivers bring sediment from the continent. The shelf off the north coast of Spain is narrow and very steep, and has few rivers bringing sediment to it. The Cantabrian Mountain range is near to the coast and forms a barrier to any drainage from the Iberian Peninsula. The sediment source, then, forms a straight line 400 miles long running in a N.W.–S.E. direction. This section of the shelf is cut by many canyons (Berthois and Brenot, 1959, Day, 1959), the biggest of which is the Cap Breton canyon at the extreme south-east end. The contours of the Biscay plain confirm that this part of the shelf is the principle source of terrigenous sediments.

Turbidity currents are, or were, initiated on the edge of this shelf and carry sediment to the plain via submarine canyons and across their deltas. While most of the currents slow down and deposit their load on the plain, some have sufficient energy to reach the south-west corner and become influenced by the drainage area of the interplain channel. Here they will be accelerated by the increased gradient and concentrated into the feeding channels. Part may over-ride the spur between channels 2b and 2a and may even go uphill into the western arm of the plain. The east facing gradient of this arm may be the result of this overshooting and subsequent slowing down, deposition and reversal of direction of the turbidity currents, or it may be due to currents initiated from higher ground to the west. If the latter were the case, the contours would imply a larger sediment source to the west of the plain than to the north or south. This seems unlikely in view of the absence of any relatively large sea-mounts in this position. If the sediments came from the west, then the absence of terrigenous sediments should be noticeable on this part of the plain. Another possibility is that there has been slight synclinal activity which has reversed the slope of an earlier formed plain.

Part of the current may be trapped by the northern channel but the contours do not suggest that much goes this way. It is possible that the northern channel is older than the southern channel and that it has since been silted up and the course of the feeding channels deflected to the south.

The main current flows along the feeding channels, shaping their bottom according to whether it is locally accelerated and eroding, or decelerated and depositing. It enters the southern channel where the sudden lateral restriction increases its velocity and it erodes down and back into the sediments of the plain. During the passage through the interplain channels its velocity will be controlled both by the gradient and the width of the channel. Erosion and deposition form the meander pattern observed. Eventually it emerges into the Iberia plain where it will flow as it did on the Biscay plain until it decays or until it reaches the deepest point. Thus sediments from the Biscay continental shelf may reach the Iberia plain and help flatten it, having travelled a distance of 600 miles. The contours of the northern part of the Iberia plain suggest that a considerable quantity of sediment has reached the plain by this route.

Similar interplain channel systems may be found wherever the sediments of one plain spill over into another. The only other example described is the Vema Gap south of Bermuda between the Hatteras and Nares abyssal plains, (Heezen *et al.*, 1959). This is 20 miles wide and 70 miles long and is in many respects similar to the one described here. The plain above the gap is cut with shallow channels which converge on the gap.

Acknowledgments—The author wishes to acknowledge the invaluable assistance of the joint senior scientists on the cruise, Dr. M. N. Hill and Dr. J. C. Swallow. The magnetic data was obtained and processed by Sir Edward Bullard and Mr. T. D. Allan. A shipboard examination of some of the core samples was made by Mr. D. H. Matthews. Finally, none of the work would have been possible without the close co-operation of the Master, officers and crew of R.R.S. *Discovery II*.

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Bottom Sediments of the Eastern Antarctic and the Southern Indian Ocean

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Abstract—During the voyage of the Soviet Marine Antarctic Expedition on the *Ob* in 1955–1957, much new bottom sediment material was obtained in the Indian Ocean sector of the Antarctic and the southern Indian Ocean. The first cores as long as 16 m in this general area were taken, as well was many more up to 4 to 5 m long. Although detailed studies have not yet been completed, it is nevertheless possible to make a preliminary report on the development and properties of the main types of sediments and the rate of sedimentation at present in this part of the Antarctic. There are also some data on the thickness of 'iceberg' and diatom sediments.

WORK at the beginning of this century resulted in a number of classical papers (MURRAY and RENARD, 1891; MURRAY and PHILIPPI, 1908; PHILIPPI, 1910) on the bottom sediments in the southern Indian Ocean. These were the basis for other investigations and have been supplemented by data from later expeditions. Nevertheless our knowledge of the Indian Ocean sector of the Antarctic is still inadequate. For example, no long cores have previously been taken there. Hence, new material on the geology of the sea bottom obtained by the U.S.S.R. Marine Antarctic Expedition, 1955–1957, is of special interest (Fig. 1).

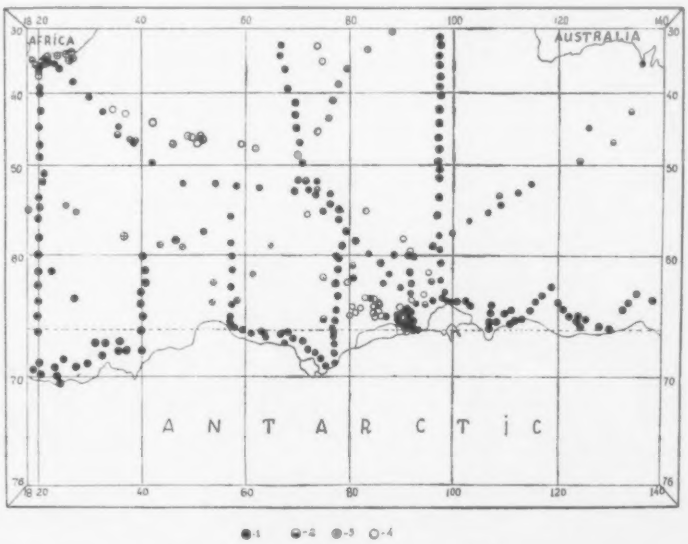

FIG. 1. Chart showing the locations for all geological stations in the southern Indian Ocean. 1. Soviet Marine Antarctic Expedition, 1955–1957 on the *Ob*. 2. *Challenger* Expedition, 1873–1876. 3. *Valdivia* Expedition, 1888–1889. 4. *Gauss* Expedition, 1901–1902.

Recent sedimentation in the southern Indian Ocean south to Antarctica* is characterized by complicated and peculiar features. The sediments in long cores obtained on two voyages of the Soviet Marine Antarctic Expedition show considerable changes in the physical and geographical conditions in this area throughout the Quaternary period. The chief Recent features are :

1. An almost complete absence of run-off from the continent, the snow-line being at sea level.
2. Extremely little chemical weathering as water on the continent is only in a solid state. Hence, the disintegration of rocks occurs only by mechanical means.
3. The negligible role of wave erosion, due to the ice barrier along the coast where there are only occasional outcrops of bedrock. For the most part outcrops are covered by shore and pack ice.
4. An absence of Recent vulcanism in the eastern part of this sector (except in the vicinity of the Balleny Islands). There is evidence of it, however, in the western part and of some seismic activity.
5. Little chemical precipitation of sediments, as the cold Antarctic waters preclude the precipitation of calcium carbonate.
6. The tremendous glacial discharge and erosion, the chief agents in transporting sediments from the land.
7. The luxurious growth of phytoplankton, especially near the ice edge and in the convergence zone. Diatoms are the chief source of the organic matter in the sediments†.
8. The rugged topography on which the sediments are accumulating. These are distributed by currents almost unaided by wave action.

Near the coasts of the eastern Antarctic continent, glaciers transport a great amount of coarse stone from the land as well as smaller material down to a fine 'glacial milk.' These result from mechanical disintegration. This glacial material is derived chiefly from the old metamorphic rocks, i.e., various gneisses, crystalline schists and granites, but with some sedimentary rock of the Beacon series (sandstones, slates, argillates). Such sediments may be spread over tremendous areas when the glaciers descend to the sea and calve. These icebergs reach 40–50° South, and sometimes even farther North.

Most of the glacial material is distributed along the routes of the icebergs and by bottom currents. Wave motion is negligible as waves are damped by the floating ice surrounding the continent. Where the ice is absent the depth of the water greatly exceeds the effective wave depth.

In the Antarctic, unlike other areas, most of the sedimentary material accumulates away from the coasts, in accordance with the maximum unloading by icebergs. Consequently, most of the accumulation from the glaciers (icebergs) falls on the

*The limit of Antarctic waters lies 900–1200 miles north of the continent and is determined by the position of the Subantarctic Convergence or Polar Front.

†Benthic organisms are relatively unimportant here.

outer part of the shelf and on the continental slope. Inshore, then, where sedimentation is slow, the shelf has a rugged topography, almost bare of sediments. This is evident not only from the bottom relief, but also from the thickness of the sediments.

Still farther offshore, the amount of glacial material decreases and diatoms become the dominant factor in sedimentation. Although more diatoms are produced in the zone where iceberg sediments are deposited, as shown by studies of suspended matter and by data on productivity, their fragments are carried out by the currents beyond the limits of the shelf, precipitated and quickly mixed with considerable quantities of glacial material, also being deposited there.

Farther north these sedimentation processes are replaced by the usual agents of oceanic sedimentation. In the zone of the Subantarctic islands, the chief source of sediments is the result of wave abrasion. Wave action and currents in the ' roaring forties ' are so great that volcanic islands are usually asymmetrical. Thus, on the west, the vertical cliffs are undercut while on the east they slope more gently. At some distance from the islands, the sediments are mostly diatomaceous, but farther north, there are planktonic Foraminifera. Sediments in the Southern Indian Ocean derived from the African and Australian continents are inconsequential due to the vast arid areas in their interiors. Most important here is coastal wave abrasion and fragmented desert sands transported by the wind.

On sheet 339 of the USSR Hydrographic Office there are a total of 385 stations, of which 225 stations were taken during the Marine Antarctic Expedition (Fig. 1). These make it possible to show in some detail the distribution of the chief bottom sediments in the southern Indian Ocean down to the Antarctic continent itself. In addition to these stations the bottom indications on the navigational charts were also used in our compliations. The following types of bottom sediments (Fig. 2) were found :

1. Terrigenous sediments from icebergs, from the Subantarctic islands and from the continental coasts in more temperate latitudes.
2. Volcanic sediments in regions of Recent volcanic activity and from Quaternary volcanoes of the Subantarctic area.
3. Sediments of organic orgin, siliceous diatom shells and sponge spicules and calcareous Foraminifera, Bryozoa and mollusc shells.
4. Chemical sediments such as phosphoritic concretions, glauconite and iron-manganese concretions.
5. Deep-sea red clays.

These sediments are similar to those recorded earlier (Murray and Renard, 1891; Murray and Philippi, 1908; Philippi, 1910; Hough, 1956). In charting bottom sediments, the Institute of Oceanology, U.S.S.R. Academy of Sciences, now uses a complex classification to indicate both their material composition and size. Later, when more data on their granulometry are available, the scheme (Fig. 2) will have to be revised.

Among the terrigenous sediments are those transported by iceberg corresponding to the earlier marine-glacial sediments (Philippi, 1910). Among bottom sediments associated with ice we differentiate : (1) marine ice, (2) icebergs, (3) marine-glaciers

(submarine moraines, which preserve their morphological characteristics (Lisitzin, 1958)). Marine deposits derived from old and winter ice have not been encountered in the Indian sector of the Antarctic, except in small patches near the coasts of some Subantarctic islands.

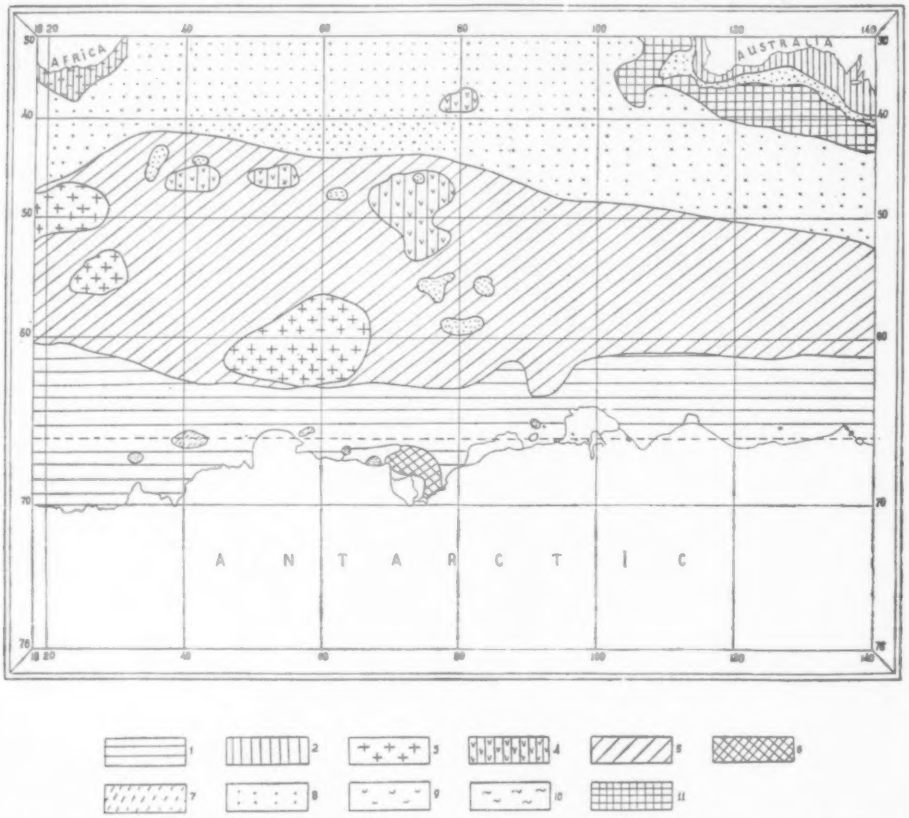

Fig. 2. Chief types of bottom sediments in the southern Indian Ocean. *Terrigenous sediments:* 1. Iceberg sediments, 2. In temperate latitudes and around subantarctic islands. *Volcanic sediments:* 3. Recent volcanic areas, 4. from Quarternary volcanoes of the Subantarctic. *Sediments organic in origin:* (siliceous) 5. diatoms, 6. Clayey-diatoms from the Antarctic continental shelf, 7. Sponge spicules. (calcareous) 8. Foraminifera, 9. Bryozoa and shells. *Chemical sediments:* 10. Phosphoritic concretions and glauconite. 11. *Red deep-sea clay.*

Iceberg sediments, which are intimately associated with wandering mountains of ice often lasting 10 years or more, surround the Antarctic continent in a solid band, practically covering the entire continental shelf, slope and adjoining parts of the ocean bed. The width of this band of sediments varies from 200–600 miles, perhaps averaging 300–400 miles, depending on the rate of calving of the icebergs and on their sediment load, as well as on the ' unloading ' process. The minimum width of these deposits lies between Enderbury Land and Lars Christensen coast, where the continental ice does not extend to the ocean coast.

The rapidity for the transformation of iceberg material to bottom sediments can be estimated by the distribution of coarse clastic material in the sediments.

Only ice can transport coarse stones* to depths of hundreds and thousands of meters, where fine-grained sediments are ordinarily developed (Fig. 3). From more than 150 determinations of such concentrations of stone, it appears that most icebergs dump their load south of 40–50 °S. The position of the isoline for 1 kg/m³ corresponds to the average iceberg limit, based on many years of observation. Stones may be the chief or permanant component in iceberg sediments.

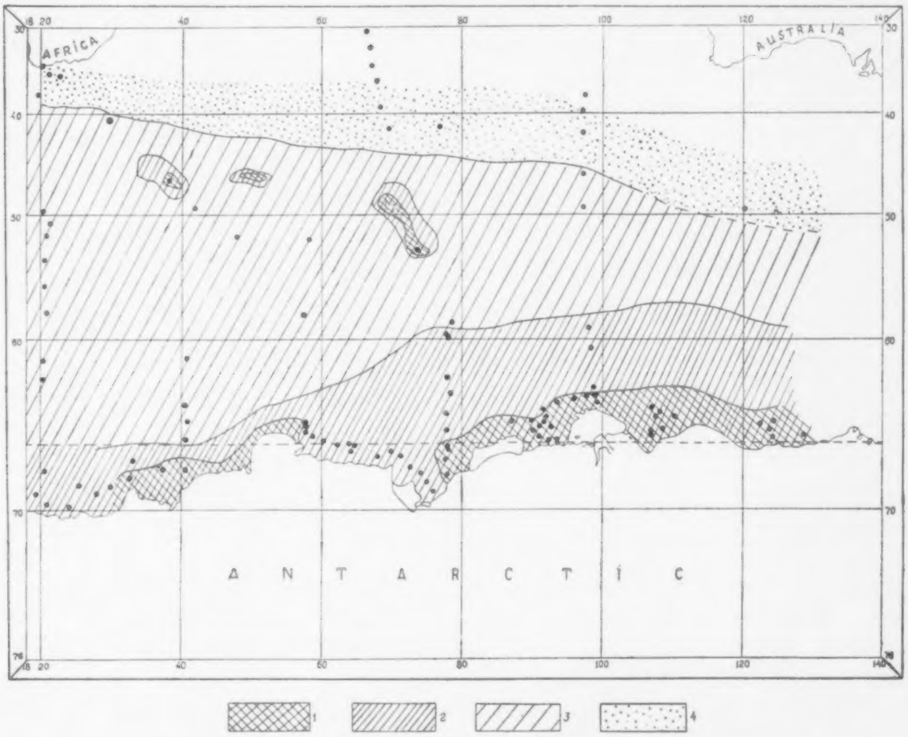

FIG. 3. Distribution of stones in bottom sediments of the southern Indian Ocean (in kg. per m³ of surface sediments – 0–20 cm). 1. More than 100 kg/m³. 2. From 10 to 100 kg/m³. 3. From 1 to 10 kg/m³. 4. Less than 1 kg/m³.

In the zone of iceberg sediments it is possible to differentiate angular stones, coarse and fine sands, coarse and fine silts, silty-clayey and clayey muds. On the shelf, coarse sediments from angular stones and down to silts are widely distributed. However, over its deeper parts and on its outer stretches they give way to fine silty-clayey and clayey muds mixed with coarse particles. There are also outcrops of bedrock. On the gentle inclines of the continental slope, there are various muds, but on the steeper parts there are coarse sediments or bedrock outcrops. Coarse sand has also occurred in samples from the continental slope, as well as from submarine elevations at depths down to 2500–3000 m. The southern parts of the ocean floor are mostly covered by fine iceberg sediments and only on elevations are they replaced by coarse

*The concentration of stones is defined as the amount of stones larger than 1 mm in 1 m³ of bottom sediments from a surface layer collected with a snapper (LISITZIN, 1951).

sediments. Iceberg sediments are usually olive-green, greenish-gray, gray and sometimes brown. They are slightly alkaline with a pH between 7·1 and 7·8, usually 7·4. They are slightly oxidized, with an E_h of $+$ 60 mV. On rare occasions only reduced sediments with an E_h of 0 to $-$ 3 mV have been found. The values of interstitial water may be as great as 63 per cent, depending on the grain size. The weight of dry sediments is usually 1 g/cm^3 to 1·8 g/cm^3.

From field and laboratory work it was possible to establish several mineral provinces in the iceberg sediments in the eastern part of the sector. The content of the various heavy minerals varies from 1–5 per cent with a maximum of 20 per cent (sp. weight over 2·70). Their greatest concentrations are along the Discovery and Knox coasts. In a number of places up to 70–90 per cent of the total consist of garnet, hornblende and ore minerals. Small quantities of stress minerals (up to 3 per cent) and numerous other less important minerals have also been found.

The following terrigenous-mineralogical provinces have been established for the eastern part of the shelf :

(1) garnet-ilmenite-amphibole (Depot Bay and Davis Sea).

(2) garnet-ore (Schackleton Shelf).

(3) ore minerals and limonite (Knox coast).

(4) amphibole-limonite-zircon with orthoclase (Sabrina coast).

(5) amphibole-epidote-zircon (Banzare Bank).

A peculiar complex of minerals including ore, olivine and an abundance of volcanic glass is typical for the Balleny Islands area.

Iceberg sediments are virtually devoid of carbonates (0–10 per cent $CaCO_3$, usually 0·1–1 per cent). Similar values have been obtained for $MgCO_3$. The Antarctic region is interesting because no organic matter is produced on land, but rather it all grows in the sea. The organic carbon content varies from 0·05 per cent to 1 per cent and is usually 0·3–0·5 per cent. It increases on the lower part of the continental slope where the fine organic detritus is transported beyond the limits of the shelf into the adjoining abyss. This can be traced very clearly by studying the suspended matter in the vertical sections near the slope. By fluorimetric-bituminological analysis, oily, pitchy and light bitumens amounting to from 1 to 20 $\times$ 10^{-4} have been found. The content of amorphous silica in two-stage soda extracts in the zone of iceberg sediments usually varies from 1 to 20 per cent, i.e., they are subsilicious. The chief sources of amorphous silica are diatoms and glass sponge spicules widely distributed on the shelf and regular components of iceberg sediments. In some places, the sponge spicules are so abundant that they become the chief component of the siliceous sediment. The iron content is usually from 2–4 per cent and increases in amount towards the foci of Recent vulcanism. The concentration of titanium is from 0·2–0·4 per cent.

From a petrographic study of stones and minerals in arenaceous-aleuritic fractions, it is possible to learn the geological structure of the coasts hidden from direct observation by the ice mass, a thousand metres thick. Thus, the submarine geology is exceedingly important in extending our knowledge of the continent itself. Very interesting data were obtained from the spores and pollen in the bottom sediments. In

sediment samples from areas adjacent to the ice-covered coasts, there are spores and pollen of ferns, birch, alder, conifers and the Myrtacease, from the Carboniferous, Permian, Triassic, Jurassic, Cretaceous and Tertiary periods. The variety of spores and pollen is shown by the fact that in a core 14·5 m long about 60 species were found, including 34 ferns, 22 gymnosperms and 4 angiosperms. There is no doubt that under the thick ice of the Antarctic continent, there are vast expanses of rock outcrops of past geologic ages containing great quantities of spores and pollen. With the disintegration of these rocks by the ice, they are transported far out into the sea, where the spores and pollen are deposited in the bottom sediments. Thus, the character and age of the rock hidden under the ice, as well as the paleogeographical conditions during the period of their deposition are ascertained.

From the vertical distribution of diatoms and Foraminifera in the cores, a positive determination of the age of the various layers can be traced for great distances. The mineral and grain composition of the sediments, as well as their chief chemical components also varies considerably vertically. This is associated with the fundamental stages of the Quarternary in the Antarctic.

The maximum thickness of iceberg sediments exceeds 14·5 m. The rate of sedimentation within this zone varies considerably. According to the latest determinations in the cores obtained from the lower part of the continental slope and from the adjoining part of the ocean bed in the area off the Totton and Adele Land coasts, the rate of their formation is 2–5 cm in 1,000 years (shown by the ionium method).

Terrigenous sediments of temperate latitudes and the Subantarctic islands fringe the coasts of Africa and Australia. They are also developed around island bases (Macquarie Island, Auckland Island, etc.). These sediments are described in sufficient detail in the literature and we therefore omit further discussion of them here.

As already mentioned (LISITZIN and ZHIVAGO, 1958 a, b) volcanic sediments are widely developed in the Indian Ocean sector of the Antarctic. These make it possible to distinguish between areas of Recent and Quaternary vulcanism. At the present time three large areas of Recent volcanic sediments are known : north of Enderbury coast, east of Trals Island (the existence of the island itself is doubtful), and, finally, south of the African continent (47–52 °S). The ' Meteor ' and ' Ships ' elevations and possibly Maude and Schmitt-Ott Banks indicate a continuation of this belt into the Atlantic Ocean, possibly in the vicinity of the Scotia Island arc. In the south, the area of Recent volvanic activity approaches the coast close to the Antarctic continent, for instance, near the Cooke Peninsula, but it usually ends between 60–65 °S. To the east of the Kerguelen–Gaussberg submarine mountain range, no products of Recent vulcanism have been found in the sediments. except in the vicinity of the Balleny Islands, where ash and lava outcrops of Recent origin occur over extensive area.

The area of Recent vulcanism coincides with that of the diatom sediments. This explains why volcanic products, chiefly of submarine origin are usually mixed with varying numbers of diatom frustules. For instance, at Station 251, south of Africa, the light diatom material is mixed with numerous dark brown and black patches of sinder, lapilli, pumice and vesicular lava. The ashy portion of the sediments is 30–40 per cent and sometimes even up to 60–70 per cent. Quite often volcanic glass ' dolls ' and ' coatings ' of a dark brown colour are found. Less frequently, they are colourless. Volcanic cones rise here up to 1000–2000 m. The nearest land, Bouvet

Island, is 600 miles away from this station. It is built of basalts and trachytes. Indeed, hot springs are found on the island.

The second region of Recent volcanic activity, smaller in extent, lies east of Trals Island, where at depths of 4600–5500 m, the surface layer is volcanic sand. Feldspars, augite, hornblende, as well as volcanic glass and fragments of volcanic rocks are dominant. Diatoms comprise about 20–30 per cent of the sediments. Ash was also collected in this area by the *Valdivia* Expedition in 1888–1889.

The area of vulcanism north of Enderbury Land occupies an area 700–800 miles long and about 600 miles wide. Submarine volcanoes rise here to 2000–2500 m above the bottom. At depths down to 5000 m, there is an extensive ash deposit which is dominantly brown volcanic glass, feldspar, augite, with a small quantity of hornblende. One core obtained by a piston corer reveals ash bands in a 440 cm-layer. For a great distance echograms continually trace two to five layers of volcanic material in these sediments.

In the vicinity of the Balleny Islands, the volcanic ash and sand consist chiefly of black uncrystallized ash, basaltic glass, magnetite, olivine, and less commonly, of amphiboles and pyroxenes. Thus, these minerals indicate that this is quite a distinct province of Recent vulcanism. On the whole, however, Recent volcanic sediments in the Indian Ocean sector are basaltic.

In the Subantarctic area, sediments of Quaternary volcanoes cover the bases of the islands west of 80 °E. All these islands were formed by active volcanoes during the Tertiary and early Quaternary periods. The last outbursts of vulcanism took place at the end of the Quaternary. On the bases of these islands are products derived from the erosion of old volcanic structures, typified by rounded grains and fragments of calcium carbonate shells, mixed with young pyroclastic material. Hence, these sediments can thus be termed terrigenous-volcanic.

The Antarctic portion of the Indian Ocean is an area of classical diatom sediments which in some cases have only 1–5 per cent of minerals. The width of the zone of diatom oozes varies from 600 to 1200 miles, and decreases toward the east. Farther north diatoms are replaced by Foraminifera in the sediments, with a boundary in the middle of the iceberg zone. This closely approaches the convergence.

Diatom sediments occur at various depths and are creamy, almost white, more rarely brownish with a typical clotted structure. When wet, they are elastic, but when dry they are easily broken up between the fingers and are very lightweight. On submarine elevations they also contain Foraminifera and gradually change into foraminiferal sediments. Diatom sediments, in contrast to those derived from icebergs are neutral with a pH value from 6·8 to 7·5. High positive E_h values are typical up to + 175 mV. The water content is greater than 60 per cent and in a number of cases exceeds 80–85 per cent. Characteristically they are also light in weight. Dry sediments weigh 0·4–0·9 g/m^3, and in some cases even less.

From their granular composition, most diatom oozes are a silty-clay or clayey-muds with up to 60–80 per cent pelite. In the silty-fraction diatoms dominate, with separate grains of minerals, Foraminifera, Radiolaria and sponge spicules. The minerals in diatom oozes are determined by the mineral complex of the iceberg sediments to the south, but the content of the heavy fraction is 5–10 times less. The mineral complex and the appearance of minerals indicates that they have been transported for a great distance by icebergs derived from glaciers along the coast.

The thickness of diatom oozes varies considerably with a maximum of about 5 m, although it is usually much less. The rate of accumulation for the southern part of the zone varies from 10–20 cm in 1000 years in the convergence zone (based on preliminary data).

The calcium carbonate content changes drastically from south to north. In the southern part, the sediments contain about 10 per cent $CaCO_3$, but its concentration increases rapidly up to 30–50 per cent on approaching the Subantarctic Convergence (Fig. 4). The sediments become predominantly carbonate and are of foraminiferal

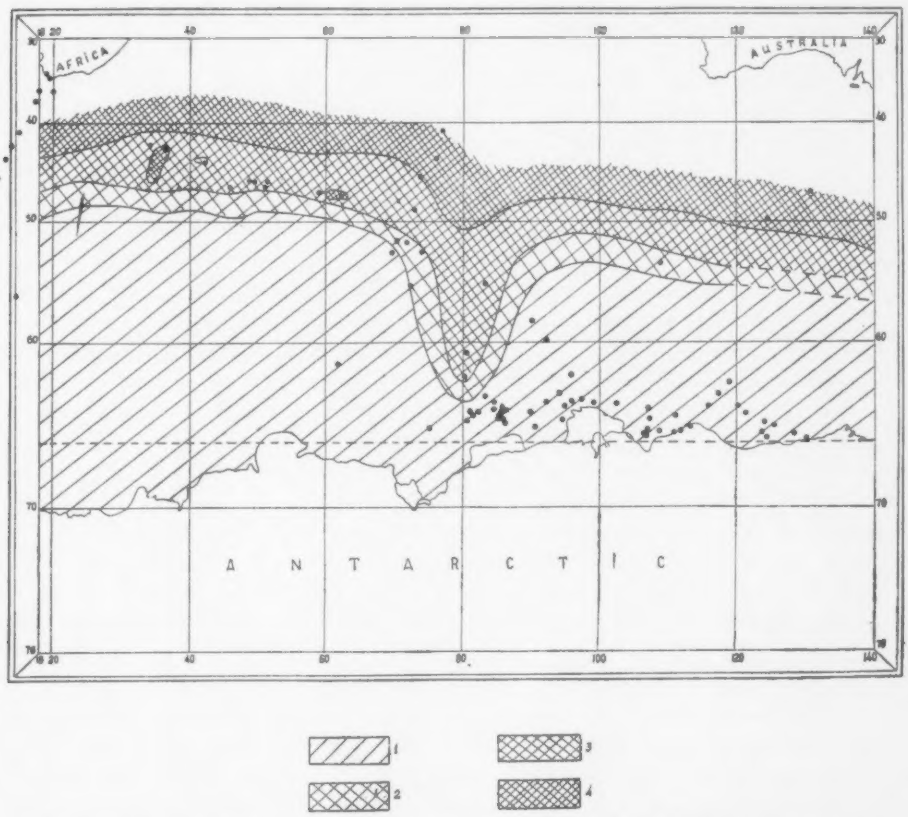

FIG. 4. Distribution of calcium carbonate in bottom sediments of the southern Indian Ocean. 1. Less than 10%. 2. From 10–30%. 3. From 30–50%. 4. Over 50%.

origin. The percentage of magnesium carbonate is not high (1–3 per cent). The content of amorphous silica in diatom oozes exceeds 50 per cent. Organic carbon is significant in these sediments and there is less bitumen than in iceberg sediments (an average of $2{\cdot}5$–5×10^{-4}). It is interesting to note a greater radioactivity in diatom oozes, 2–3 times that in iceberg sediments. Apparently, it is associated with the adsorption of radioactive compounds from the sea water.

On some portions of the Antarctic shelf and in particular in the Prydz Bay area, patches of clayey-diatom muds have been found in which the diatoms and diatom

fragments form 30–50 per cent of the sediment. These green or olive-green muds at depths of 500–700 m have a thickness up to 50 cm. Below them are typical iceberg sediments.

Siliceous sediments include also sponge spicules on the shelf at depths of 100–400 m. Muds with glass sponges, as stated above, are typical for the entire zone of iceberg sediments. In a number of places, however, they form a felt-like sediment impregnated with mud. According to BELIAEV and USHAKOV's (1957) determinations, sponges are dominant in the Antarctic benthos at depths of less than 400 m and at a number of stations they formed 96 per cent of the biomass. The apparent thickness of sediments built of spicules is 0·7–1·0 m.

Among calcareous sediments of organic origin*, the greatest extent covered by foraminiferal sediments lies beneath the northern convergence. Their extent is controlled by the depth : deeper than 4600–4700 m they are replaced by red clay. The position of the lower boundary is determined by the solubility of calcium carbonate and the physico-chemical environment in the waters of the southern Indian Ocean. Stones, so common in diatom and iceberg sediments, are absent in foraminiferal sediments, but iron-manganese concretions are widely distributed in them. These concretions are sometimes large. There are few minerals in these sediments as they are chiefly fine terrigenous and ashy materials. They are alkaline (pH of 7·4–7·5) and have only an average oxidation potential (E_h up to $+$ 210 mV). Shells of Foraminifera form up to 95–99 per cent of the total with planktonic Globigerinas dominant. In some samples, calcareous algae are important and the calcium carbonate content rises to 88–90 per cent. The rate of accumulation for these sediments (by the ionium method) is 5–8 mm in 1000 years.

Foraminiferal sediments occupy the entire central part of the Indian Ocean north of the Subantarctic Convergence. However, in some places where there are typical Antarctic sediments, foraminiferal sediments have also been found. These are usually on submarine elevations where Foraminifera accumulate, but where the finer materials are presumably swept away by the currents. In addition coarse minerals and rock fragments are transported there by icebergs. Nevertheless, these sediments accumulate slowly as is shown by the presence of iron-manganese concretions on the surface. The southernmost point where foraminiferal sand has been obtained is apparently Station 226 at a depth of 960 m on Gunnerus Bank (67° 30′S). Here about 60 per cent of the sediment consisted of well-preserved white calcareous Foraminifera.

Adjacent to the coasts of the Antarctic continent, on the shelf of Davis Sea and near Lars Christensen Coast, bryozoan sediments have been found often containing shell material. In depths of 600–700 m, samples have been almost entirely fragments of bryozoans, large Foraminifera and the tubes of calcareous worms. Samples taken with a snapper contain Recent benthic organisms and not relics of earlier warm periods. In a number of places, bryozoan sediments are mixed with sponge spicules. The latter indicate the most favourable localities for the development of the bottom fauna on the Antarctic shelf.

Red abyssal clay is found north from the convergence zone at maximum depths of the Indian Ocean, deeper than 4500–4800 m. Usually about 85 per cent or more is a pelite. The distribution of concretions in red clay is not uniform. In the central

*Beds of mollusc shells widely distributed in other parts of the World ocean, such as along the coasts of Africa and Australia, have not been found in the Antarctic.

Indian Ocean, for example, not one concretion was obtained on washing 50 l of red clay. The rate of accumulation of the red clay northwest of Amsterdam Island, as determined by the ionium method, has been 2 mm per 1000 years.

The author takes this apportunity to thank A. V. Zhivago, A. F. Beresnev, P. N. Fominykh, V. M. Basov, V. V. Shiporin, E. I. Gordeev, S. E. Alferov, A. F. Shmyrev, E. I. Sidorov and A. I. Kuvarzin for their assistance in the work during the Expedition to the Antarctic.

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Alexa Bank, a drowned atoll on the Melanesian Border Plateau

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Abstract—The Melanesian Border Plateau covers an area 1000 by 200 miles along the north-eastern edge of Melanesia, facing the Central Pacific Basin, with an average depth of 1500 fm (2700 m). It trends E–W, but is broken up into a series of narrow ridges and troughs *en échelon* trending NW–SE, each approximately 250 miles long and 100 miles from ridge crest to crest. The troughs rarely exceed 2200 fm (4000 m) in depth. Some are closed basins and others open out in a funnel shape, sloping gradually down into the Central Pacific Basin (2700 fm or 5000 m). Although the Border Plateau is bounded by the ' Andesite Line ' there is an anomalous absence of any belt of deep trenches on the Basin margin. The échelon ridges of the Plateau are mostly less than 1000 fm (1800 m) deep. They are capped by a few small volcanic islands and a large number of slightly submerged (10–15 fm or 18–27 m) atolls of dead, ' drowned ' corals. Alexa Bank is a characteristic example. The cause of coral death is a mystery; vulcanism and foul upwelling are possible explanations.

INTRODUCTION

ONE OF the most curious sectors of the Pacific margin is the Melanesian Border Plateau (Fig. 1). This area extends from about 170 °E to 175 °W longitude, between latitudes 10° and 14 °S, and is thus roughly 200 to 500 miles NW. to NE. of the Fiji Islands. Politically, the Wallis and Horne Islands belong to the French Dependencies in Oceania. Rotuma comes under the British colonial administration of Fiji, Nurakita is classified with the British colony of the Gilbert and Ellice Islands, while in the far west Anuda (or Cherry) and Mitre Islands belong administratively to the New Hebrides condominium.

The thousand-mile length of the Border Plateau is peculiar on several counts :

(a) It is oriented E–W, an altogether unusual pattern in the broad picture of the western border of the Pacific which runs roughly N–S.

(b) Its E–W trend is broken up into numerous NW–SE segments *en échelon,* little ridges and troughs, averaging 250 miles long and 100 miles from crest to crest, which, as bathymetric features, appear to be almost unique in the world oceans.

(c) It is bounded on the north by the ' Andesite Line,' but one island (Wallis) near its outermost edge, is regarded as having ' Atlantic-type ' (i.e. oceanic) lavas.

(d) The ' Andesite Line ' and Pacific margin is not bounded by a zone of deep ocean trenches as elsewhere, but generally only by a gentle slope†.

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†After these lines were written, the Soviet research ship, *Vitiaz* discovered a 6140 m deep trench, the *Vitiaz* Trench at 10° 25′S, 170° 16′E about 75 miles NNE of Anuda (Cherry) I. A modified interpretation of the feature is suggested in FIG. 1, in preference to the E–W trough depicted by UDINTSEV (1958).

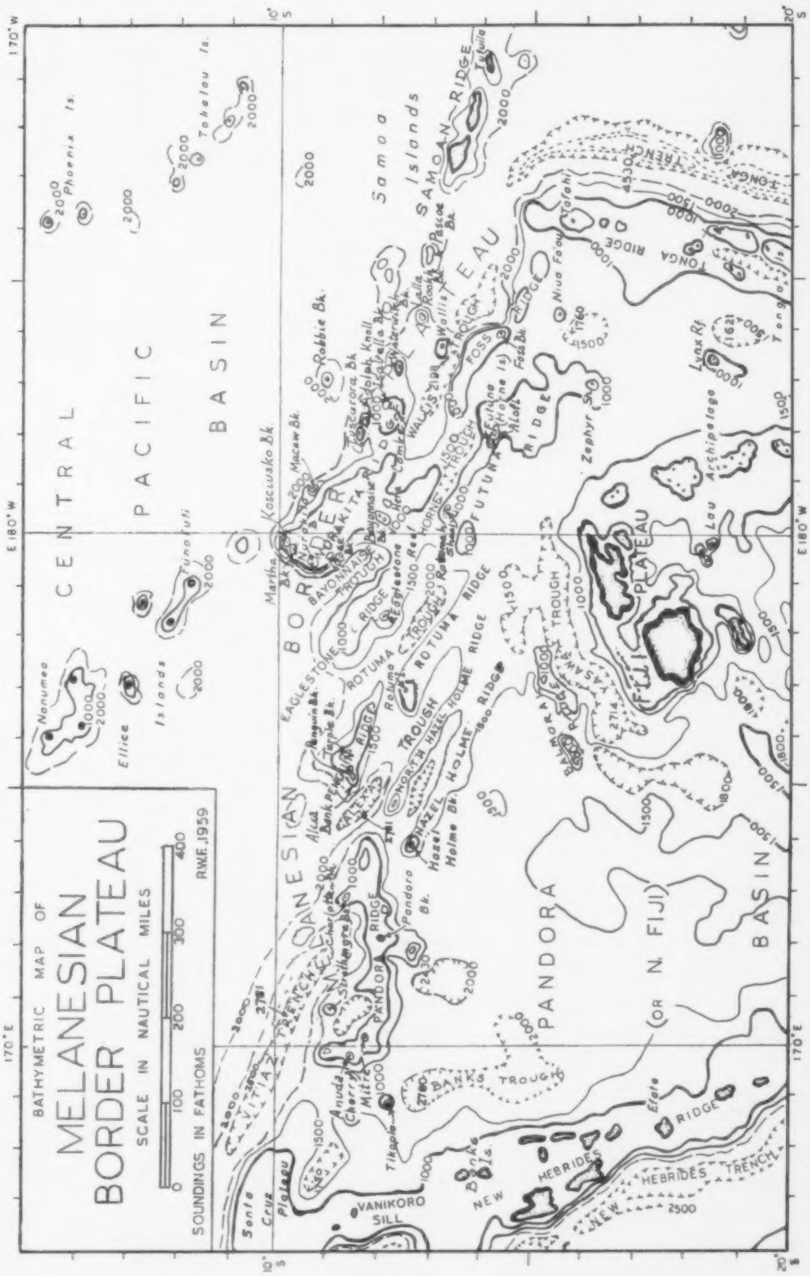

FIG. 1. Bathymetric chart of the Melanesian Border Plateau (see definition in introduction), showing location of echelon ridges and troughs, and banks representing probable drowned atolls.

(e) The *échelon* ridges are spotted by numerous 'banks' at 10–15 fm (18–27 m) which are interpreted as 'drowned' atolls. The cause of death of the corals is not yet clear.

The purpose of the present paper is to report on an echo-sounding survey of the Pacific slope, several banks (notably, Alexa Bank, also Penguin Bank and Turpie Bank, Figs. 2–3), and traverses over the Rotuma and Alexa Basins, and over Rotuma and Hazel Holme Ridges. These were carried out on Expedition CAPRICORN of the Scripps Institution of Oceanography, by the Research Vessels *Spencer F. Baird* and *Horizon* in December, 1952.

The two ships were equipped with high-frequency EDO echo-sounders reading by a vertical recording on a shoal scale of 0–600 ft, and deeper scales in 600 fm stages to over 5000 fm to an accuracy of 10 fm (18 m). Normal crusing speed was 11 knots. The ships navigated, as far as possible, on parallel courses 10–50 nautical miles apart.

A generalized contouring of the bathymetry of the Melanesian Border Plateau was carried out by the senior author at the Scripps Institution of Oceanography, La Jolla, in July–August 1954. The field work aboard the *Horizon* and the detailed map of Alexa Bank were completed by the junior author. The senior author joined the expedition at Fiji.

Our appreciation for encouragement and assistance is due to Dr. ROGER REVELLE, Director of the Scripps Institution of Oceanography and leader of the CAPRICORN expedition and to many individual members of the Scripps Institution, notably R. L. FISHER and H. W. MENARD.

BATHYMETRIC FEATURES OF MELANESIAN BORDER PLATEAU

The Melanesian Border Plateau (Fig. 1) measures approximately 1000 miles (E–W) by 100 to 300 miles (N–S). Depths of the basins are 1600 to 2200 fm (2900–4000 m) while the ridges are more or less flat-topped at 300–600 fm (556–1100 m). The mean depths of the plateau range from 1000 down to 1500 fm (1800–2700 m).

The name Melanesian Border Plateau was proposed (FAIRBRIDGE, 1960)* to designate the partially raised 'rim' of the Melanesian region. It forms the northern limit of the Pandora Basin (or the 'North Fiji Basin' of WISEMAN and OVEY, 1955, p. 101), and is separated from the Fiji Plateau (of Sir JOHN MURRAY, 1895) by the Balmoral Ridge and the Yasawa Trough (FAIRBRIDGE, 1960).

The contouring of this large and very poorly known area presents many difficulties of interpretation that cannot be satisfactorily solved until more detailed echo-sounding surveys are carried out. In the meantime, the details provided by the CAPRICORN tapes permit the establishment of a working hypothesis, *i.e.* that the basic trends or the Border Plateau are NW–SE, and not E–W as might reasonably have been assumed. With this assumption the pattern begins to unfold in a logical manner and a structural meaning appears for many isolated soundings.

However, it should be reiterated that these interpretations are based on a general hypothesis. It is not, for example, always possible to see whether an isolated shoal sounding represents a submerged bank on a general ridge or a seamount rising from

*Formal publication of this and other new names in this area first appeared in 1958, on Plate 10 of Bartholemew's Times Atlas (Mid-Century Edition), on the basis of ms. maps supplied by the senior author.

considerable depths. With these reservations, therefore, the ridges and troughs are now described for the first time.

Among the more important *Ridges* are the following :

(a) *Pandora Ridge* is 250 miles in length (E–W) extending from 11° 45′S to 12° 30′S and 169° 30′E to 174° 30′E. It apparently consists of a series of minor NW–SE elevations 50 to 70 miles long and joined together *en échelon*. It forms the most westerly element of the Melanesian Border Plateau, being separated from the Santa Cruz Plateau by a 50 miles opening which connects the northwest end of the Pandora Basin (or N. Fiji Basin) with the Central Pacific Basin. Pandora Ridge is named after the Pandora Bank which lies in the middle of the ridge. This bank in turn was named after its discoverer H.M.S. *Pandora* under Captain E. EDWARDS. *Pandora* played a historic part in the search for the Bounty mutineers (1791) as well as in Pacific exploration. Other features of the ridge include Anuda (Cherry) and Mitre Islands, Strathmore, Charlotte and numerous unnamed banks and shoals, mostly of 10-15 fm (18–27 m).

(b) *Penguin Ridge* is 130 miles in length (NW–SE) and is separated from Pandora Ridge by the Alexa Trough with only 20–30 miles between the two. It is separated from the Rotuma Ridge to the southeast by a narrow sill that separates the Alexa and Rotuma Troughs. Penguin Ridge is surmounted by a number of banks and shoals, all submerged by 13–17 fm (24–31 m), and including Alexa, Penguin, and Turpie Banks (Figs. 2–3). Detailed soundings made by the *Baird* and *Horizon* indicate that the banks have saucer-shaped tops, suggestive of ‘drowned atolls’ (Fig. 3, also H.O. Chart 1984A, B.A. Chart 2901)*. The ridge is named for the middle of the three banks and also honours H.M.S. *Penguin*, which, under the command of Capt. A. M. FIELD, carried out the pioneer hydrographic surveys in this region during the year 1896.

(c) *Eaglestone Ridge* is 140 miles in length and lies some 50 miles east of Penguin Ridge. It is similar in form to the latter and can be defined by the 1000 fm (1800 m) contour. Eaglestone Reef could not be located by H.M.S. *Penguin* after a protracted search in 1896, but in 1943 a 5 fm (9 m) bank was sounded at 9° 43′S, 176° 36′E. However, although the ridge has not been thoroughly surveyed, it has an extensive top of depths of 400–600 fm (700–1100 m), so there is every possibility that other banks may be situated along the ridge. The feature is separated on the southwest by the Rotuma Trough from the Penguin-Rotuma Ridges and on the east by the Bayonnaise Trough from the Nurakita Ridge.

(d) *Nurakita Ridge* lies 50 miles north-east of the Eaglestone Ridge and trends equally NW–SE. It is 300 miles in length with a mean depth of 700 fm (1300 m) but is separated into more subsidiary rises, domes and furrows than most of the other ridges. It should be noted that it forms the extreme north-eastern limit of the Melanesian Border Plateau, paralleling the border of the

*H.O. refers to U.S. Navy Hydrographic Office charts and B.A. to British Admiralty charts.

Central Pacific Basin which drops sharply away to 2500–3000 fm (4500–5500 m). The Nurakita Ridge is crowned by two islands, Nurakita at the extreme north-western end and Wallis in the extreme southeast. Between, there are numerous banks and shoals, including Rose, Martha, Kosciusko, Macaw, Bayonnaise, Tuscarora, Adolph, Hera, Coombe, Isabella, Waterwitch, and Lalla Rookh. An interesting feature of these, and other unnamed banks is that they all rise to the very constant depth of 10–16 fm (18–29 m), approximately the same depth as the banks crowning Pandora and Penguin Ridges (H.O. Charts 0087, 1993; B.A. Charts, 1829; 1830).

(e) *Foss Ridge* lies south-east of the Nurakita Ridge and may be interpreted possibly as a long-distance extension of Eaglestone Ridge. As here defined it is 200 miles long, trending NW–SE with mean depths ranging from 800–1100 fm (1500–2000 m), generally about 900 fm (1645 m), thus notably lower than the western ridges. Foss Ridge, like Nurakita, forms the edge of the Melanesian Border Plateau and is separated from the parallel Samoan Ridge which lies less than 100 miles to the NE across an enclave of the South-West Pacific Basin. The only shoals that nearly reach the surface of the Foss Ridge are Foss Bank, with 22 fm (40 m), and another bank (reported in 1943) just south of it rising to $4\frac{1}{2}$ fm (8 m) (B.A. Charts 1829, 1830).

(f) *Hazel Holme Ridge* forms one of a second series of *échelon* ridges and troughs that lie about 50–100 miles south of the series Pandora–Penguin–Eaglestone–Nurakita. Hazel Holme Ridge is about 250 miles long trending WNW–ESE with apparently two parallel crests separated by a narrow furrow; northerly one is distinguished as 'NORTH HAZEL HOLME RIDGE.' The *Baird* and *Horizon* crossed these features on two traverses. Mean depths of the ridges are about 1000 kms (1800 m), and only one bank, Hazel Holme itself, rises to 17 fms (31 m); this bank has the same 'drowned atoll' form as the banks of the Penguin Ridge type (see H.O. Chart 1984B, or B.A. Chart 2901).

(g) *Rotuma Ridge* lies 25–50 miles east of Hazel Holme Ridge, trending WNW–ESE. It is 200 miles long with mean depths of the order of 1000 fms (1800 m) and is crowned by Rotuma Island and an unnamed 14 fm (25 m) bank, both at the north-west end. It is well defined by the 1500 fm (2700 m) contour. The traverses by the *Horizon* over the northern side of the ridge to Rotuma confirmed a remarkably steep off-shore profile (H.O. Chart 1984; B.A. Chart 1829).

(h) *Futuna Ridge* lies farther to the east and may perhaps be regarded as an extension of both Hazel Holme and Rotuma Ridges. It is of irregular shape extending roughly NW–SE for 250 miles in depths of 700–900 fms (1280–1450 m) (B.A. Chart 1829). It is crowned by the Horne Islands of Futuna and Alofi, with isolated shoals including Rotumah Shoal* in the north-west, and others including the Zephyr Shoal in the south-east. Rising as an isolated cone 50 miles to the east is the intermittently active volcano

*Not to be confused with Rotuma Island, 200 miles to the west.

Niua Fo'ou ('Tin Can Island'); however, it is doubtful if this island lies on the Futuna Ridge.

Turning next to the minor basins, troughs, or furrows between the elevated ridges of the Melanesian Border Plateau, there may be distinguished the following :

(i) *Alexa Trough* is a narrow depression, 200 miles long, trending NW–SE between Pandora and Hazel Holme Ridges in the south-west and Penguin and Rotuma Ridges on the north-east. There are also east–west furrows separating each ridge of each pair. The floor of the trough slopes down from 1500 fms (2700 m) in the south–west to 2200 fms (4000 m) in the north–west, where it reaches 2781 fm (5084 m). The basin is named after Alexa Bank to the north whence it falls away very sharply (Fig. 7a).

(ii) *Rotuma Trough* is parallel to and generally similar to the Alexa Trough, though somewhat broader, lying between Rotuma Ridge and Eaglestone Ridge. It is 150 miles long and includes a closed area east of Rotuma of more than 2000 fm (3650 m). To the north–west it opens into the Central Pacific Basin. R. V. *Horizon* traversing this part of the trough found a very even gradient down into the Central Pacific Basin (at about 10 fms per mile, or 1 : 100). This clearly is a case of an axially tilted trough where an emergence would expose a 'rias' coastline (the British National Committee on Ocean Bottom Features informally suggested 'seafirth' for such features, but the term has not found much favour).

(iii) *Bayonnaise Trough* is a third parallel furrow, separating Eaglestone from Nurakita Ridges. It is broader and shorter than the other troughs, being only 100 miles long and 50 miles wide. Its floor slopes from 1500 fms (2700 m) in the south–east to 2400 fms (4400 m) at the opening into the Central Pacific Basin. This is another case where the term 'trough' or 'basin' may well be replaced by another generic term, such as 'seabight.'

(iv) *Wallis Trough* lies in the same trend as Bayonnaise some 150 miles to the east–south–east. Its central part is a very narrow depression, completely closed by the 2000 fm (3656 m) contour, lying south–west of Wallis Island and north of the Foss Ridge. It is about 180 miles long and though the deep portion is only about 20 miles across, it widens out as it shallows to the west. Its eastern end is not well known.

(v) *Horne Trough* is oriented in a similar way and situated to the southwest and located to the north west of the Horne Islands (Futuna and Alofi). It is a very narrow depression with a portion of over 1800 fms (3290 m) completely closed. It extends over 100 miles in length and is only 10–20 miles wide.

TOPOGRAPHY OF ALEXA AND OTHER BANKS

Alexa Bank is well illustrated on B.A. Chart 2901 (H.O. 1984A) and numerous traverses by Expedition CAPRICORN add considerably to the detail (Figs. 2 and 3). Echo traces also disclose topographic features previously unknown. As shown in the illustrations (Figs. 4–7) the bank clearly has a raised 'rim.' This is generally

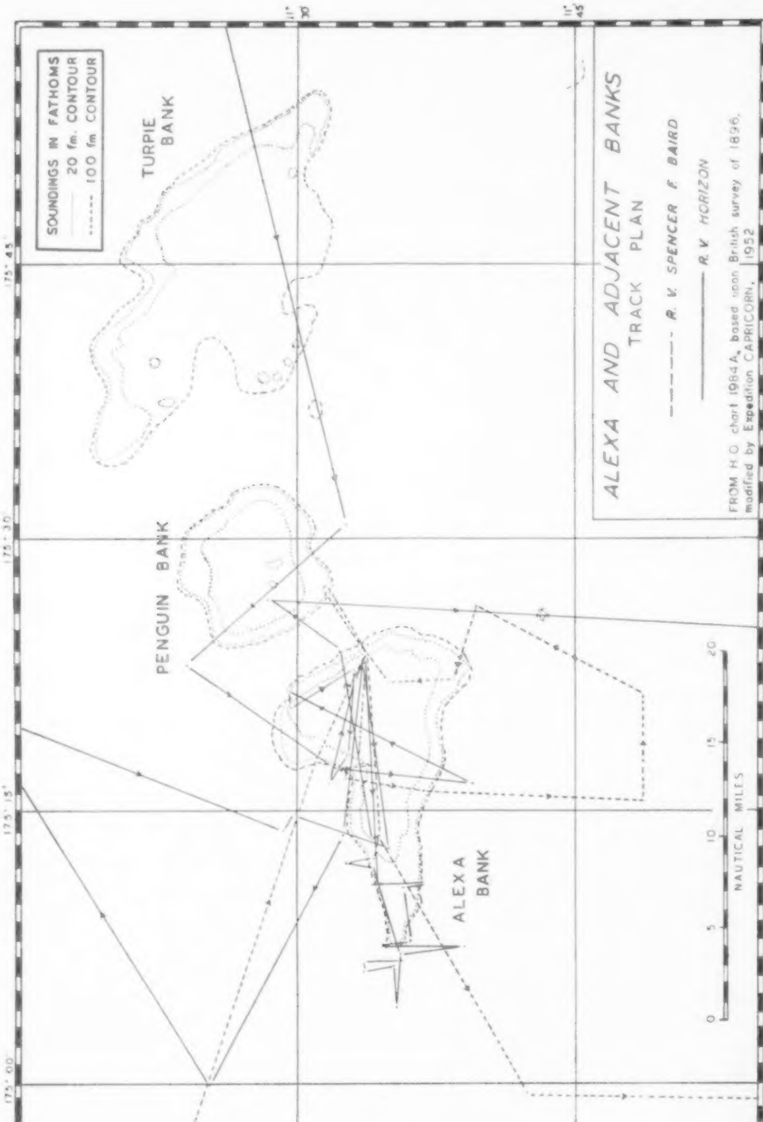

FIG. 2. Track plan for Alexa Bank area, showing routes of R. V. *Spencer*, F. *Baird* and R. V. *Horizon* on Expedition CAPRICORN, 1952. These banks are situated on Penguin Ridge (FIG. 1).

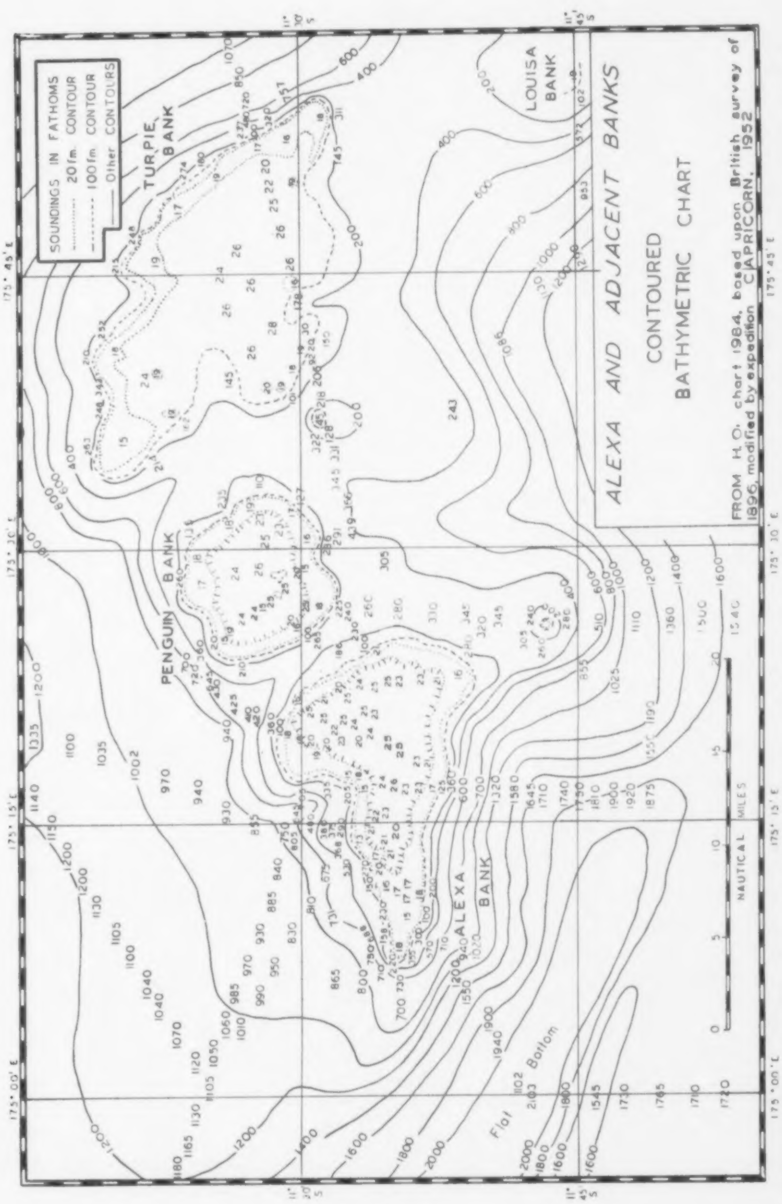

FIG. 3. Contoured bathymetric chart of Alexa and adjacent banks, based on early surveys and CAPRICORN echo soundings. These banks are situated on Penguin Ridge (FIG. 1).

1000–2000 feet wide and is 30–60 feet above the level of the flat saucer-like depression over the centre of the bank. There appear to be three distinctive levels : (a) 60–70 ft (10–12 fm or 18–21 m), the ' Rim '; (b) 90 ft (15 fm or 27 m), an intermediate terrace; on the inside it is about 2000–3000 ft in width, but on the outside it is 0–300 ft in width; (c) 120–130 ft (20–22 fm or 36–40 m), the main terrace (floor) of the bank.

In places over the surface of the rim and on the floor of the bank there are pinnacles or knolls rising 10–20 ft. Investigations with the aid of an ' aqualung ' proved that these were in part living coral heads, but that the rest of the bank was covered by dead coral boulders encrusted with algae and covered with a white calcareous (foraminiferal) mud.

Some pinnacles of exceptional size, 30 ft high or more (Fig. 5a) could represent living coral heads, but, lacking confirmation, an alternative hypothesis must also be entertained. If the banks are essentially erosional features (see below, ' Pleistocene Karst Effects '), the pinnacles may in part be erosional remnants of karst solution.

The outer margins of Alexa Bank steepen very sharply and drop away to great depths at remarkably steep gradients. Angles of 30–40° are maintained on these slopes for thousands of feet. Dredging was unsuccessful on these slopes, but there seems no doubt that the only rock type strong enough to stand up at such angles without collapsing would be a massive coral limestone. Admittedly the spine of a volcanic cone will maintain steeper slopes, but the size of Alexa and other banks here (5–20 miles across) precludes a simple volcanic plug. We have no sample or geophysical evidence* which would indicate whether or not there is a volcanic core to each of the banks but the fact that several volcanic plugs (Anuda, Wallis, Horne, etc.) do occur in the area is suggestive.

Expedition CAPRICORN traversed Alexa, Penguin and Turpie Banks, which were all of the same type. The hydrographic charts suggest that there are more than forty such banks in the Melanesian Border Plateau. In dimensions, Alexa Bank is an average one measuring 10 miles by 5 miles across; Penguin Bank is about 4 miles by 4 miles.

Turpie Bank is also 10 miles by 5 miles, but most of its rim on the south–west side is missing; the rim terrace is mostly at 15–20 fm, and the main bank 26–27 fm. Tuscarora Bank is about 12 miles by 8 miles and its rim is broken in many places, and is of similar depths. Robbie is about 10 miles by 10 miles, has a perfect rim at 10–12 fm and an interior flat about 26–27 fm. Pascoe is nearly 30 miles long but only 2–5 miles across, with a rim at about 10 fm and interior terraces at 20 and 27 fm. Most of the others show this sort of pattern, though a few rise to 4–5 fm.

SUBMARINE BANK TERRACES

Hitherto the only author to comment at any length on the banks of the Melanesian Border Plateau was R. A. DALY (1934, p. 241 ff.), who concluded that the accordance of terrace depths between these (and other platforms in different parts of the world) required a common explanation. He suggested that low-sea level planation during Pleistocene glacial stages was the only acceptable hypothesis; local subsidence seems to require altogether too remarkable coincidences over such a very broad area.

*Dr. Russell Raitt (personal communication) notes that his incomplete seismic data suggests a volcanic core to Alexa " roughly similar to Funafuti atoll."

Fig. 4 (a). Surface of Alexa Bank, showing giant fan corals growing from an otherwise 'dead' surface, covered with fine calcareous mud and algal covered boulders. 'Aqualung' diver is Prof. Walter Munk. Photograph by Scripps Institution of Oceanography.

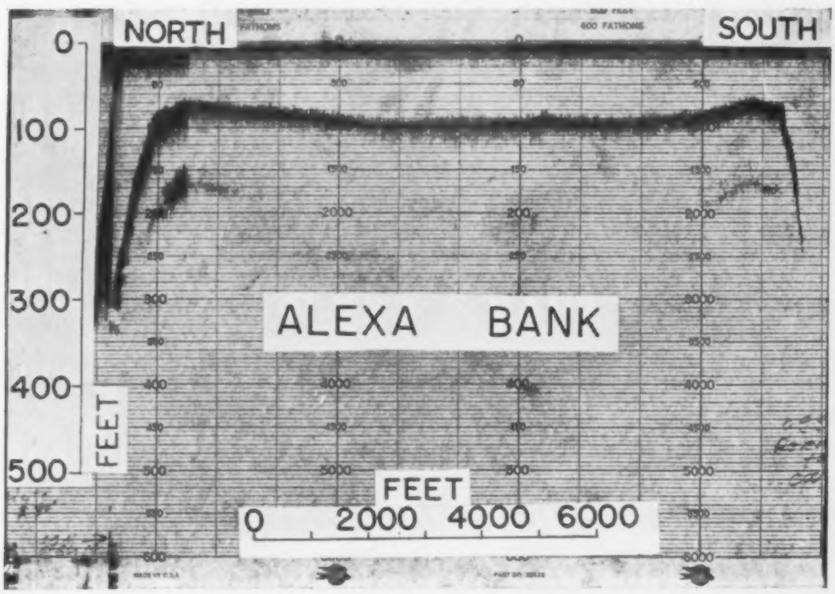

Fig. 4 (b). Echo-sounding trace by R. V. *Horizon* across the top of Alexa Bank, near the west end. Note rims of the bank at 60–70 ft, with saucer-shaped depression at 90 ft.

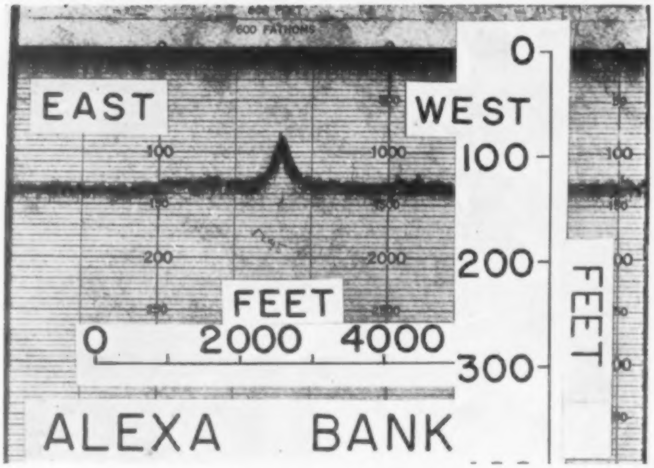

FIG. 5 (a). Surface of Alexa Bank, echo-trace by R.V. *Baird* in the deepest sector near the east center : average depth here 130 ft. Pinnacle rising 30 ft from floor may be interpreted either as a coral knoll that has grown up, or as a karst residual.

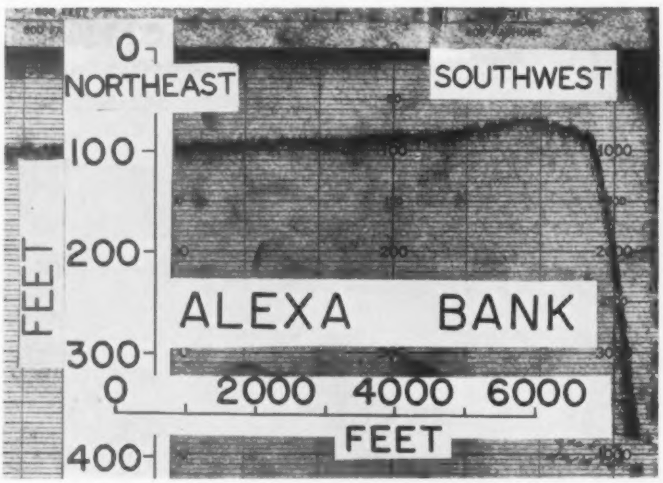

FIG. 5 (b). Detail of southwest rim of Alexa Bank, echo-trace by R.V. *Baird*, showing humped shape of rim 1800 ft wide, and abrupt offshore slope, dropping 500 ft in 900 ft of traverse, a gradient of 1 : 18 (30°).

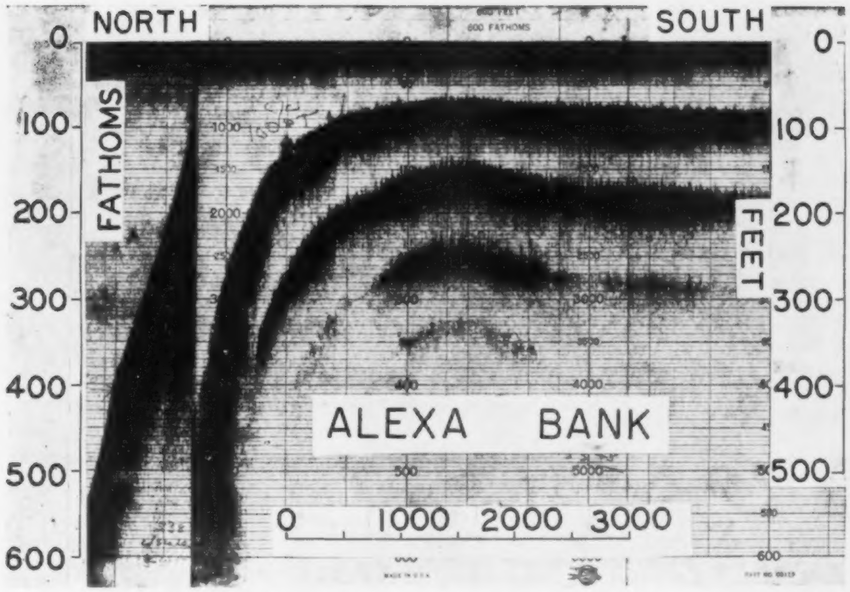

FIG. 6 (a). Northern rim of Alexa Bank, showing unusual rounded profile, with rim at 65 ft, dropping to 80 ft towards the interior of the saucer. Small coral heads seem to mark the outer edge in 70–120 ft. Offshore gradient (on fm scale) is 36° steepening at 1000 fm (course change) to 40°.

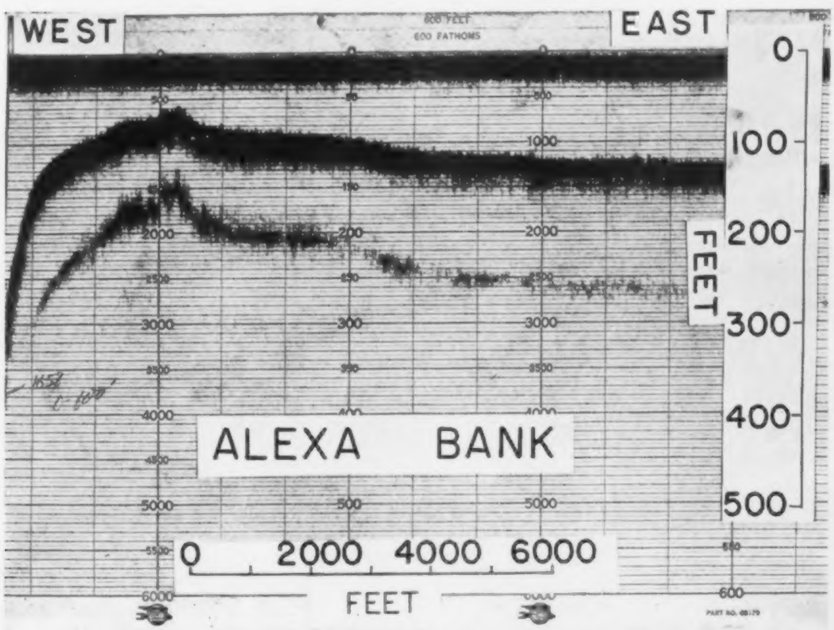

FIG. 6 (b). Northwest rim of Alexa Bank, showing traces of two terraces levels in saucer-like platform, the rim at 70 ft, rising in pinnacles to 60 ft, an inner terrace at 90 ft, and the platform floor at 120–130 ft.

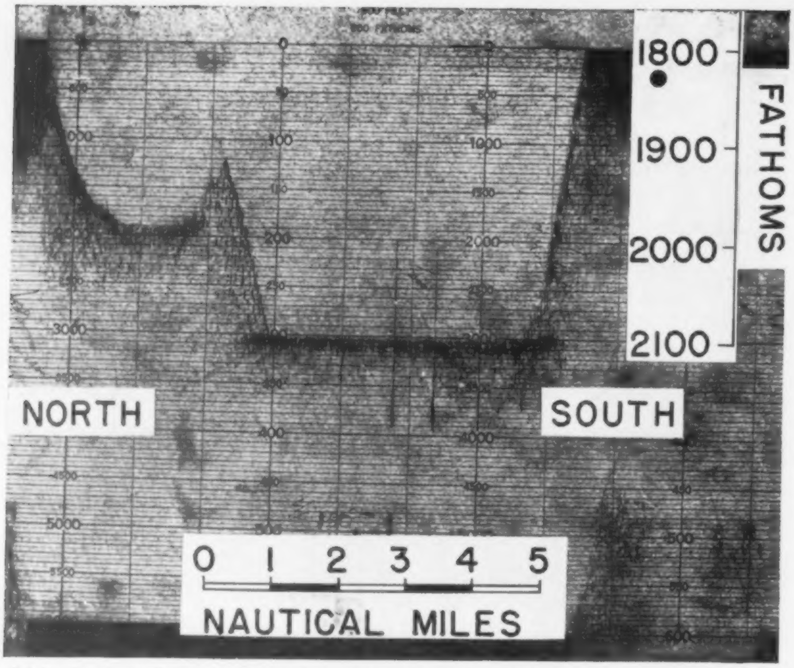

FIG. 7 (a). Section of the flat floor of the Alexa Trough at 2100 fms. The lower slopes of the trough exhibit a gradient of 1 : 25 (22°). An intermediate step is shown at 2000 fm, sediment being apparently dammed back by a low ridge.

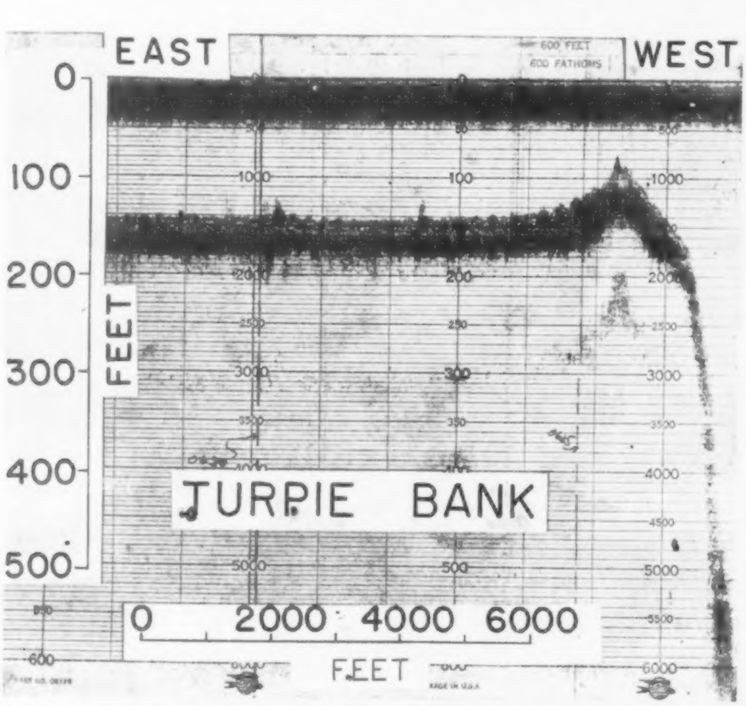

FIG. 7 (b). Margin of Turpie Bank, another drowned atoll on Penguin Ridge. Note that the inner side of the bank is steeper than at Alexa Bank, dropping from 70 ft rather steeply to a uniform floor at 140 ft, punctuated by small coral heads or knolls rising 10–20 ft above the floor.

We agree with Daly's interpretation in general, but with some modifications. There appear to have been not one but several periods of planation, as there are several distinctive terrace levels. They are so wide-spread that they probably call for a eustatic explanation; 10–12 fm (18–21 m), 14–17 fm (25–30 m), and 25–27 fm (46–50 m) seem most constant.

Some local, but minor tectonic forces may be involved in some of the areas, where a slight tilt or segmentation seems to be involved. The region is now almost completely free from recordable seismicity and vulcanicity, although some of the steep lower slopes, *e.g.*, the 22° slope dropping straight down into Alexa Trough (Fig. 7a), are indicative of at least a potential instability.

There are no direct data for the terraces but if they are rather youthful there may not have been time for slow secular tectonic changes to become obvious. That the terraces are indeed youthful is suggested by the smooth fresh surfaces and the relative freedom from youthful coral overgrowth.

Recent studies by one of us (Fairbridge, 1958) assisted by radiocarbon datings, carried out by the Lamont Geological Observatory, Yale Geochronometric Laboratory and the U.S. Geological Survey, clearly indicate that important eustatic oscillations and still-stands occurred even during the post Glacial (Recent) epoch, notably at minus 3–4 m or 1½–2 fm (in several oscillations dating back to 4300 B.P.*), at about − 21 m or 12 fm (8500 B.P.), at − 32 m or 18 fm (11,000 B.P.) and at − 46 m or 25 fm (12,500 B.P.).

From the evidence available it would seem that deeper eustatic terraces ranging from 20 to 75 fm are to be correlated with low sea-levels of the last Glacial (Wisconsin/Würm), as may be seen from the data of the Mississippi delta, where a factor of local subsidence is also recordable (Fisk and McFarlan, 1955). Consideration of the general, secular drop of sea level through the Quaternary (Zeuner, 1952) suggests that the low sea-levels of glacial stages earlier than the Wisconsin would not have reached much lower than the present sea-level. This concept is quite contrary to that of Daly (1934) who visualized an equal drop of sea-level for each successive glacial age. Some evidence, admittedly not conclusive, is presented by Emery (1958) for terrace cutting in southern California earlier than the Wisconsin but here the picture is considerably complicated by warping. Emery has also provided a valuable bibliography of recent data on submarine terraces that confirms our first impression that the levels observed on Alexa and adjacent banks are to be found repeated in many parts of the world, and are therefore most reasonably interpreted as eustatic.

PLEISTOCENE KARST EFFECTS

There is little doubt that coral banks subject to late Pleistocene exposure due to a drop in sea-level underwent intensive karst solution. Such effects are most striking in reefs associated with the marginal latitudes of the coral-favoring environments : thus Bermuda (32°N), Bahamas (25°N.), Pescadores (23°N), Houtman's Abrolhos (29°S). Submarine terraces, channels and ' ocean holes ' are characteristic features. In the days of the Murray-Darwin controversy the solution effects were taken (by the Murray school) to be the product of contemporary erosion by sea-water. Following A. Agassiz (1903, p. 412) : ' The existence of honeycombed pinnacles of limestone within the lagoons of atolls, as shoals, islands, or islets, shows the extent

*B.P. = before the present (datum year A.D. 1950).

of the solvent action of the sea upon land areas, having formerly a greater extension than at the present day.' But according to modern studies, carbonate solution by sea-water seems possible only in the intertidal belt, except under special circumstances (Revelle and Fairbridge, 1957).

Subaerial solution is thus inevitable. In any hypothesis it is therefore essential to provide for the total emergence of any coral platform to permit deep-reaching karst solution. 'Ocean holes' (karst sink holes) dropping down hundreds of feet are observed in the Bahamas (Agassiz, 1894) and in the Houtman's Abrolhos (Fairbridge, 1948, see esp. pl. 3), and Jordan (1954) has described similar features at 140–150 fm on the east Florida shelf.

To quote from the Abrolhos description (Fairbridge, 1948, p. 30): 'During the Würm exposure, the island must have stood up as a fairly high eminence, about 350 ft above sea level. Deep reaching karst erosion set in and the whole of this limestone mountain became riddled with sink-holes, underground streams, caverns, stalactite caves, and the like. It is probable that the margins of this table-topped mountain were higher than the centre, though the rim may well have had gaps in the north.'

The development of submerged terraces on coral banks and atolls is particularly striking (as opposed to the less obvious terracing of continental shelves) because of the low rate of sedimentation in oceanic areas. Certain continental areas with marginal to arid hinterlands also show the same features but they are less usual (see the West Australian shelf profiles, Carrigy and Fairbridge, 1954).

Fine examples of bank terraces are to be seen in the Tonga Islands, especially north of Tongatabu and west of Ha'apai, both of which were traversed by Expedition Capricorn. Well-developed examples can be seen also in the South China Sea, e.g. Macclesfield Bank and Tizard Bank (Spratley Is. or Tua Sha Is.) where they are described by Wharton (1888) and Kuo (1948); also in the East Indies, e.g. Tijger and Paternoster Banks (Molengraaff, 1930; Kuenen, 1933, 1947; Umbgrove, 1947); again in the Maldives and Laccadives (Gardiner, 1903). Few, however, demonstrate such barren simplicity as those of the Melanesian Border.

In a laboratory tank, Hoffmeister and Ladd (1945) subjected an exposed block of limestone (with a flat-cut top) to a continuous shower of dilute acid, to simulate rainfall during the last Glacial low sea-level period. The similarity to the effects of subaerial solution was remarkable: the block became lined with characteristic karst runnels down the sides, but the top was only slightly lowered and in a *saucer-shape*. An atoll-like rim was thus produced by a purely solvent process. Many elevated islands have precisely this form today (Hoffmeister and Ladd, 1935). MacNiel (1954) proposed that such solution effects produced during low sea-level stands could explain the form of modern atolls generally. This may be true, but owing to the heavy post-Glacial overgrowth of coral on the rims and accumulation of sediment in the lagoons, it cannot always be demonstrated.

Special consideration is needed to explain how terraces occur on the rims of modern, growing atolls (e.g. Bikini; see Emery *et al.*, 1954), of emerged atolls (*e.g.* on Kita and Minami Daito or N. and S. Borodino Islands: see Nugent, 1948; Saplis and Flint, 1949; Fairbridge, 1950b), and of submerged atolls, such as on the Melanesian Border Plateau. If, after the last Glacial low period, as the sea rose to a still-stand at 8 fm (9000 B.P.), coral grew vigorously over the old eroded rim to the

new level, it would then spread out to the limit of the foundation, within the depth range for the organism concerned. The sea-level then dropped to 12 fm (at 8500 B.P.). For several centuries the margins of the rim were then eroded, and became notched, forming terraces. At the same time new reef fringes built up these terraces at their periphery. Those coral communities facing the interior of the atoll built up more rapidly than those facing the outer margin, contrary to popular belief. Wider reef flats are found on the inner side, because the bottom is shallow there and permits rapid lateral growth while on the outer face the floor drops away steeply and much outward growth is impossible. This tendency has been confirmed by ground studies and from air photographs of many reef platforms (Fairbridge, 1950a; Teichert and Fairbridge, 1950); in the waters of atoll lagoons, which are changed daily by tidal currents, there is no convincing evidence of greatly restricted coral metabolism due to nutritional deficiency (thanks largely to the photosynthetic activity of the symbiotic algae, zooxanthellae : Sargent and Austin, 1954).

Coral upgrowth with rising sea-level continued after 8500 B.P. This was followed by alternate periods of terrace-cutting and lateral growth, repeated several times with diminishing amplitude to make the steep-like margins of atolls.

The reason for failure of most of the coral banks on the Melanesian Border Plateau to maintain up-growth to the present level is still a mystery. The terracing of the rims is not as sharp as is usual on emerged atolls and perhaps indicates a poverty of coral growth during the still-stands. Some of the profiles are very similar to Hoffmeister and Ladd's (1945 and to MacNiel's (1954) sketches, suggesting that solution has greatly dominated over coral growth during the last 15,000 years.

DISCUSSION : THE DROWNING ATOLLS

W. A. Setchell (1928, p. 325) once remarked : 'the general, although tacit, assumption that the submerged reef is living seems to be taken for granted,' indeed, without any real grounds at all. Setchell (1928) found that many of the submerged reefs, particularly in Hawaii, the Fijis and Tonga, were just as dead as the emerged reefs. Corals can be killed by a few hours of exposure above tide level, but it is not always appreciated that they can be wiped out almost as easily by a rapid submergence which may bring them into depths that are too cool or too dark for normal growth. This may be due either to local subsidence or to a very sudden eustatic rise in sea level. Such a rise took place near the beginning of the Recent epoch, when apparently the sea level rose 90 ft within a period of a few hundred years (according to recent radiocarbon dates). This may have exceeded the growth and adaptation rates of the corals concerned. Some of the subsequent, though smaller sea-level changes were even more rapid (Fairbridge, 1958). Under such conditions one speaks of corals as having been 'drowned,' but the physiological and environmental factors responsible for this are not well established. Under favourable conditions a number of coral species have an astonishing temperature and depth tolerance, as witness the deepwater reefs of the coast of Norway, Ireland and Spain (Pratje, 1924; Teichert, 1958).

The 'drowned' coral banks of the Melanesian Border Plateau lie between 11° and 13°S and thus are clearly equatorial. It is therefore improbable that their death reefs could be explained by lower sea temperatures during the last Glacial age. Coral farther from the equator (say 25–30°N and S) may well have been affected in that

way, but the Melanesian Border Plateau is hardly a marginal latitude with respect to coral habitat.

DALY (1934) visualized Pleistocene planation by wave action as more vigorous than today. Furthermore the large amount of sediment in suspension would inhibit much of coral growth (DALY, 1934). In the continental shelf areas near the ecologic limits of coral growth this concept seems well-substantiated, but sediment suspensions are not to be expected in this part of Melanesia, many hundreds of miles even from the nearest major island groups (Fiji and New Herbrides) and 1500 miles or more from the nearest continental rivers in eastern Australia.

Quite distinct from the killing and erosion of the coral communities during the last Glacial stage is the major problem why, during the subsequent rise of sea-level, corals did not colonize the eroded platforms and grow upwards to form contemporary atolls and living coral banks. The scattered coral colonies on the surface of the banks today suggest a highly improverished or only recently colonized habitat.

There are at least five possible explanations worth considering :

(a) During the last major drop of sea-level, fringing reefs failed to maintain themselves on the margins of the coral banks. These were certainly very steep and offered an extremely restricted and narrow biotope. Block-faulting and landslides could have carried many colonies down into cold, dark, inhibitory depths. During the subsequent rise in sea-level there were no established colonies to generate upward growth to develop and maintain a normal atoll.

(b) The location of the Melanesian Border Plateau is an isolated region, not easily replenished by young coral planulae from protected, favourable 'nurseries' (GUPPY, 1903–06; WELLS, 1957). It lies within the South Equatorial Current which skirts the islandless region north of the Marquesas, Tahiti and Samoa, swinging southwestwards into Melanesia. In Glacial times this current may have been much cooler than today. Isotope temperature determinations by EMILIANI (1955) suggest 5° to 8° lower mean surface water temperatures. An additional factor to the general lowering of solar radiation was the contribution in the east from the cold Humboldt (Peru) Current, fed by the great Pleistocene glaciers of the Chilean Andes and the advanced ice-front of Antarctica.

(c) The Melanesian Border Plateau is situated in the region of the Southeast Trade Winds, which are only periodically reversed in summer by the northerlies or Northeast trades. This would mean that most of the time (especially in the cool Pleistocene period) it would be downwind of the volcanoes of Tonga and Niua Fo'ou; some of the youthful volcanic sources of Fiji or the Wallis Islands (now extinct) may also then have had active phases. Showers of volcanic dust coupled with a lowering of sea-level would be deleterious to coral growth. However, experimental work by YONGE (1940) and colleagues on the British Museum's Great Barrier Reef Expedition suggests that the importance of sedimentation in discouraging coral growth has been exaggerated in the past. This 'explanation' is therefore discounted.

(d) As noted above, the narrow *échelon* troughs of the Melanesian Border Plateau are almost unique in contemporary marine geology. They compare

most obviously with the ' Continental Borderland ' of southern California. Even the newly discovered *Vitiaz* Trench (Fig. 8), with its oceanside rim higher than the floor of the Central Pacific Basin, suggest ' borderland ' tectonics, rather than the marginal trench characteristic of the western Pacific. These borderland trenches and troughs include numerous narrow closed

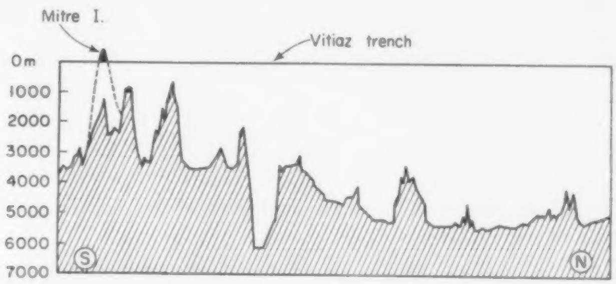

FIG. 8. North-south profile through the Melanesian Border Plateau along long. 170° 16′E, crossing Pandora Ridge just east of Mitre Island, and the newly discovered *Vitiaz* Trench (from UDINTSEV, 1958). Note the location of the trench *within* the borderland.

depressions, which would favour the development of foul bottom in black mud facies inhabited only by anaerobic bacteria. The production of H_2S by the latter would probably lead to periodic upwelling of lethal waters (BRONGERSMA-SANDERS, 1957).

(e) Another possible form of upwelling is the type due to the impact of onshore currents on steeply rising continental margins (SVERDRUP, 1938; FLEMING and REVELLE, 1939). The Melanesian Border Plateau is in fact a continental margin. Here the Central Pacific Basin is about 2700–2000 fm deep, and the bottom slopes steadily up to the banks of the Plateau. The South Equatorial Current flows southwesterly here, thus directly onto the *échelon* slopes of the banks which extend NW–SE. Unfortunately we lack water samples and temperature observations in the critical areas to prove the existence of such upwelling.

TECTONIC POSITION OF THE MELANESIAN BORDER PLATEAU

The situation and structural pattern of the Melanesian Border Plateau is anomalous from many points of view. According to MARSHALL (1911), BORN (1933) and others it represents the subcontinental margin of the Pacific and is bounded by the ' Andesite Line.' Volcanic material in Fiji, and in the few volcanic islands of the Border Plateau mostly point to ' Pacific Suite ' (*i.e.* Pacific margin) petrology. BRYAN (1944), however, drew his ' Marshall Line ' rather differently from BORN (1933) to exclude the Melanesian Border Plateau, swinging it around Fiji and the New Hebrides, and leaving the Pandora Basin and the whole Border Plateau in the Mid-Pacific province. It is doubtful if BRYAN was correct, however, as the shallow ridge and basin areas can hardly be classified as typically ' mid-Pacific.' The lavas from most of the islands confirms BORN's (1933) viewpoint. Earlier reports by VIALA (1919), DE LA RUE (1935) and LACROIX (1941) suggested that all the volcanics were of the Circum–Pacific olivine basalt.

However, MACDONALD (1945, p. 870) demonstrated that a single centre, the Wallis Islands (notably Uvea), ' undoubtedly belong to the alkaline suite of the central Pacific volcanoes ' (*i.e.* ' Atlantic Suite ' of HARKER). This is unusual since the Wallis Islands are situated within the Border Plateau. However, the orientation of the echelon ridges here exactly parallels that of the Samoan Ridge and other WNW–ESE mid-Pacific volcanoes (Cook, Tahiti, Hawaii). It is surmised therefore that some of these structures are related to deep crustal fractures, of considerable age, and less related to the new orogenic belts of the Melanesian subcontinent than to the old Pacific thlassocraton*.

In tectonic geology, it is tempting to interpret a zone of echelon structures as normal faults or short strike-slip shears, symptomatic of a great linear transcurrent (strike-slip) fault at depth. Since the *échelon* structures are oriented NW–SE or WNW–ESE, this would indicate an E–W trans-current basement fracture, of sinistral or left-lateral displacement. Thus, it would be complimentary in character to the Great Alpine Fault of New Zealand, to the San Andreas Fault of California and many others.

However, the similarity ends here, and in several outstanding points there is a marked contrast. The fundamental E–W orientation of the Melanesian Border Plateau is essentially out of line with the general NNE and NW trends of the western Pacific. It is an almost aseismic zone. It is not paralleled by a belt of deep sea trenches. It seems to fit into the broad picture of old Pacific shear patterns, but it apparently is no longer an active tectonic belt. This is supported by the geomorphologic evidence of a long period of stability in the Wallis Islands (STEARNS, 1945).

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*A term introduced by the senior author to cover the stable, oceanic type of crust (FAIRBRIDGE, 1955, p. 42).

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Geophysical investigations of a Seamount 150 miles North of Madeira

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(*Received* 28 *May* 1960)

Abstract—An elongated seamount rising to 678 fathoms was surveyed by echo-sounding, dredging, photography, magnetic and seismic methods, the results of which are described. The feature appears to be the result of volcanic extrusion along a fault running obliquely across a broad rise.

INTRODUCTION

ON 17th AUGUST, 1956, an investigation was started by R.R.S. *Discovery II* of a sounding of 825 fathoms marked on the Admiralty charts 150 miles north of Madeira Is. A radar marker buoy was anchored near the top point of the seamount and during the following three days topographic and magnetic surveys were made of the area within a radius of 15 miles; three dredge hauls, three camera stations and one seismic station were also made. During these three days the weather was ideal for carrying out these operations and no time was lost in using all the methods at our disposal to make a thorough investigation of the form and composition of the seamount.

NAVIGATIONAL ACCURACY

The marker buoy was a dan buoy bearing a radar reflector and flag, attached to a string of 9 elliptical pellets and moored to 88 lb. of iron sinkers with 2 mm aircraft wire in a depth of 740 fathoms. 870 fathoms of wire was let out allowing a horizontal scope for the buoy of about 5 cables. There was no evidence throughout the investigation of the buoy mooring having moved.

The buoy was visible on radar up to a range of 5 miles and the ship's position within this radius could be fixed to 1 cable. Beyond the range of the buoy, positions were plotted by D.R. using distances measured by log and were subsequently adjusted making corrections for a constant error in the log reading and by correcting for surface currents. The surface current corrections were based on the difference between the D.R. position at the end of a closed run and the position obtained from the buoy.

The accuracy of the tracks obtained was checked by the measurement of both the depth and the earth's total magnetic field at points where tracks crossed. In principle where two tracks are known to cross, and there are gradients of both depth and magnetic field that do not have coincident directions, the point of intersection is uniquely determined by the position of equality of both the depth and the field. It was found, however, that the bottom was so rough and the magnetic field so variable that unique intersections could not be found. But small adjustments of track were made based on these measurements in order to improve the fit. In no case was the track moved by more than half a mile.

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The position of the dan buoy was obtained by celestial observations made at seven different times during the investigation. The mean of these observations gives the position as 34° 52′N 16° 31′W with an estimated error of ± 1 mile.

Throughout the period the wind was from the west or northwest of force 2 or 3. Indications of surface current were obtained from various sources. On two occasions the direction of streaming of the pellets on the dan buoy suggested currents in the

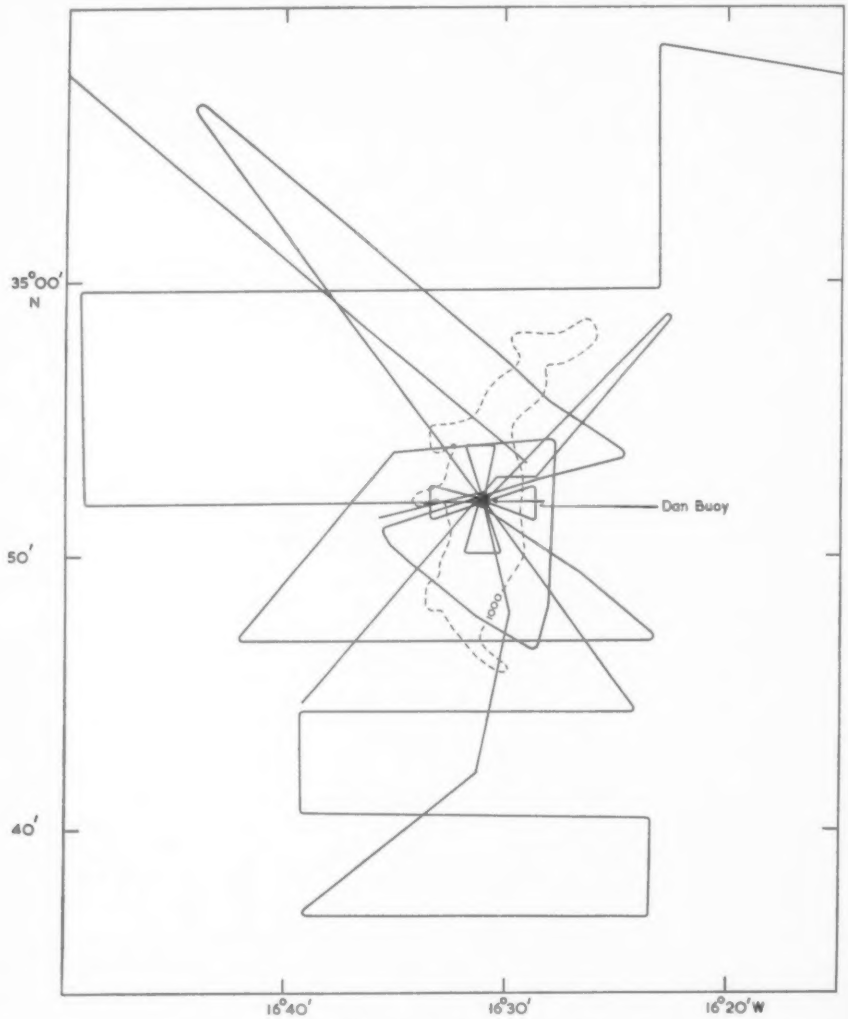


FIG. 1. Track chart of R.R.S. *Discovery II.*

directions 135 °T and 150 °T. The drift of the ship during camera station 3455 showed a current of 0·6 knots in direction 132 °T. During station 3456 there was no appreciable current. The error of closure of the survey made to the south of the dan buoy, if attributed to a current, gives a value of 0·2 knots in direction 104 °T. An un-

successful attempt was made to measure the surface current with a drogue. It is apparent from the wind and current data that the buoy was not subject to altering conditions and lay still to both wind and current within a cable or so.

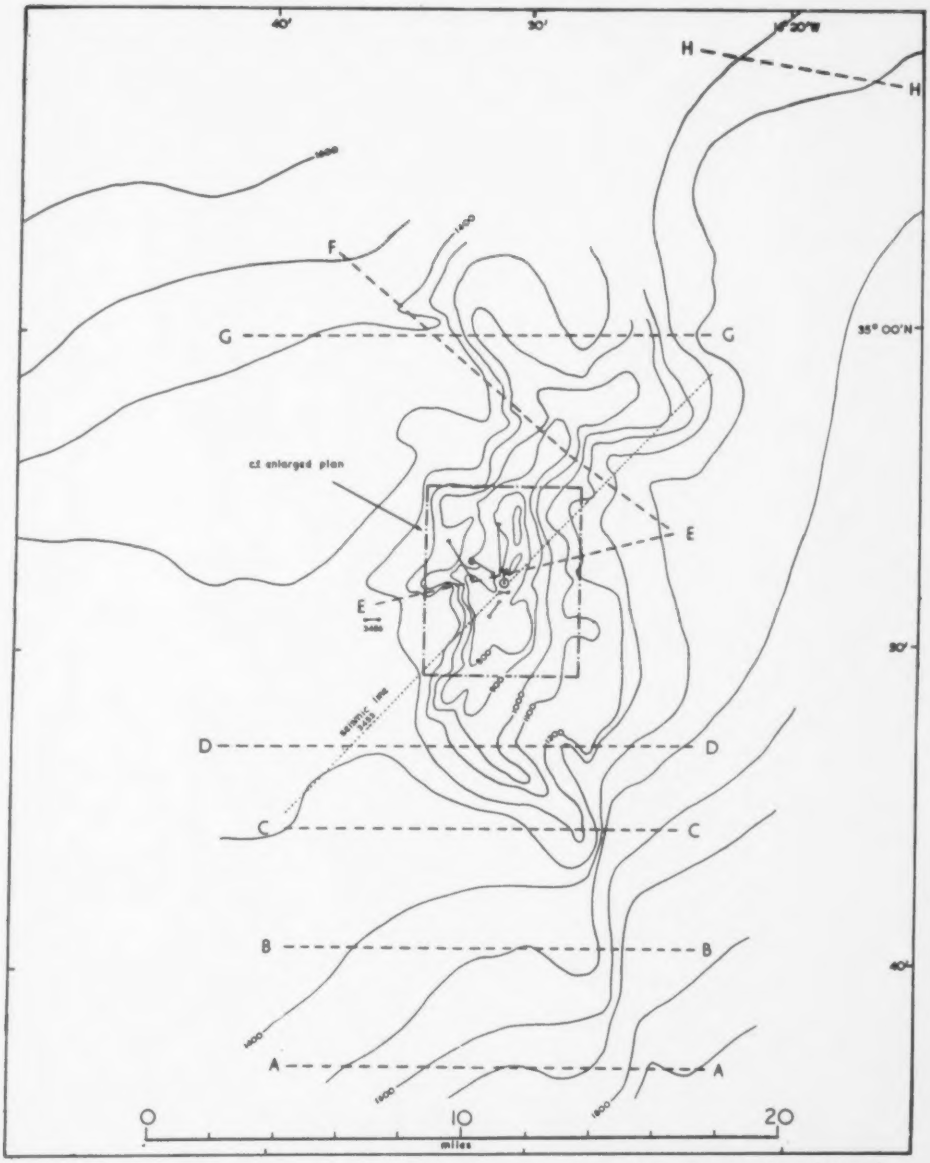


FIG. 2. Contour chart of seamount showing location of profiles and stations (contour interval 100 fathoms : soundings corrected according to HD 282).

TOPOGRAPHIC SURVEY

A Kelvin Hughes MS26E echo-sounder was used continuously to record the depth. The speed of the pen is controlled by a governer and a check was made every

half-hour by timing one revolution against a crystal clock. The soundings were read and recorded every five minutes and subsequently corrected for speed errors and also for variations in the velocity of sound in sea water according to Matthew's tables

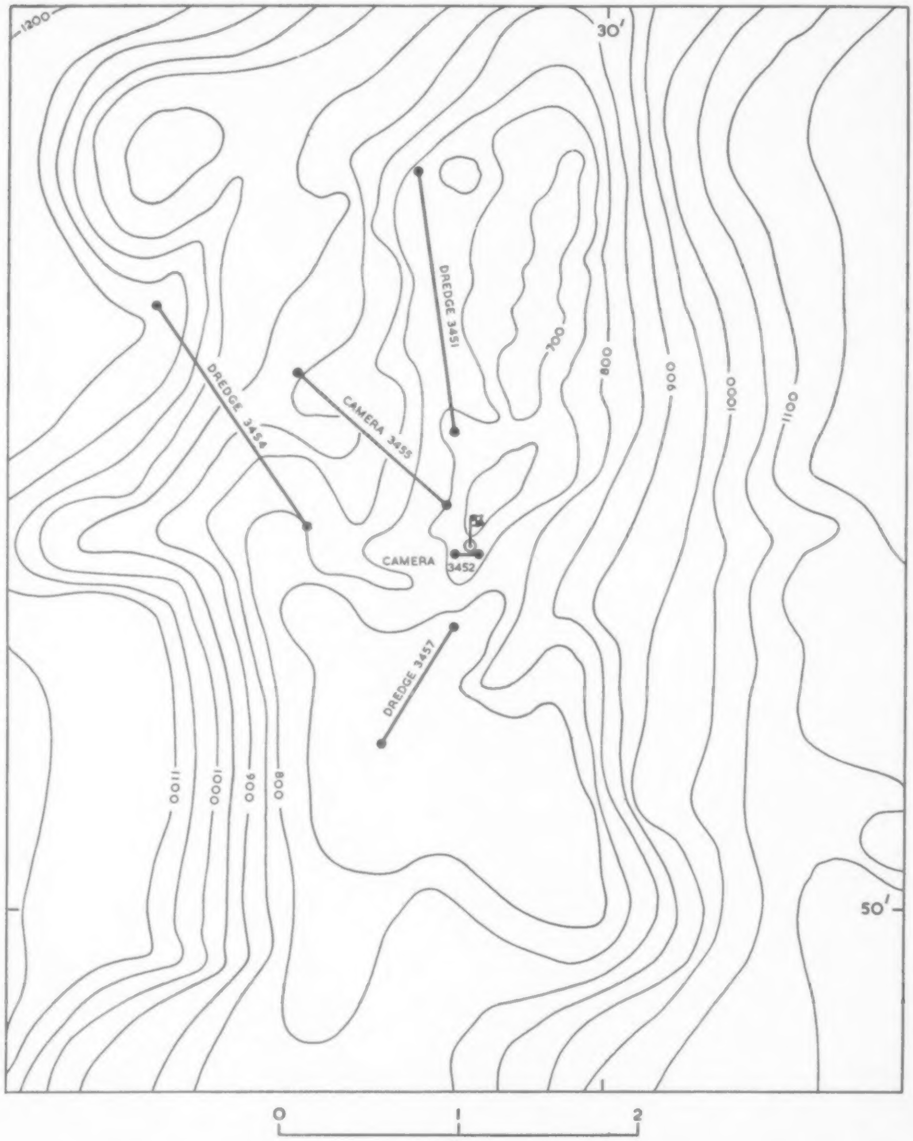


Fig. 3. Contour chart of central ridge showing location of dredge and camera stations (contour interval 50 fathoms).

(HD 282). The track chart is shown in Fig. 1. The soundings were transferred to a plotting sheet and then contoured at 100 fathom intervals (Fig. 2). A large-scale chart of the centre portion of the seamount was also prepared using a 50 fathom

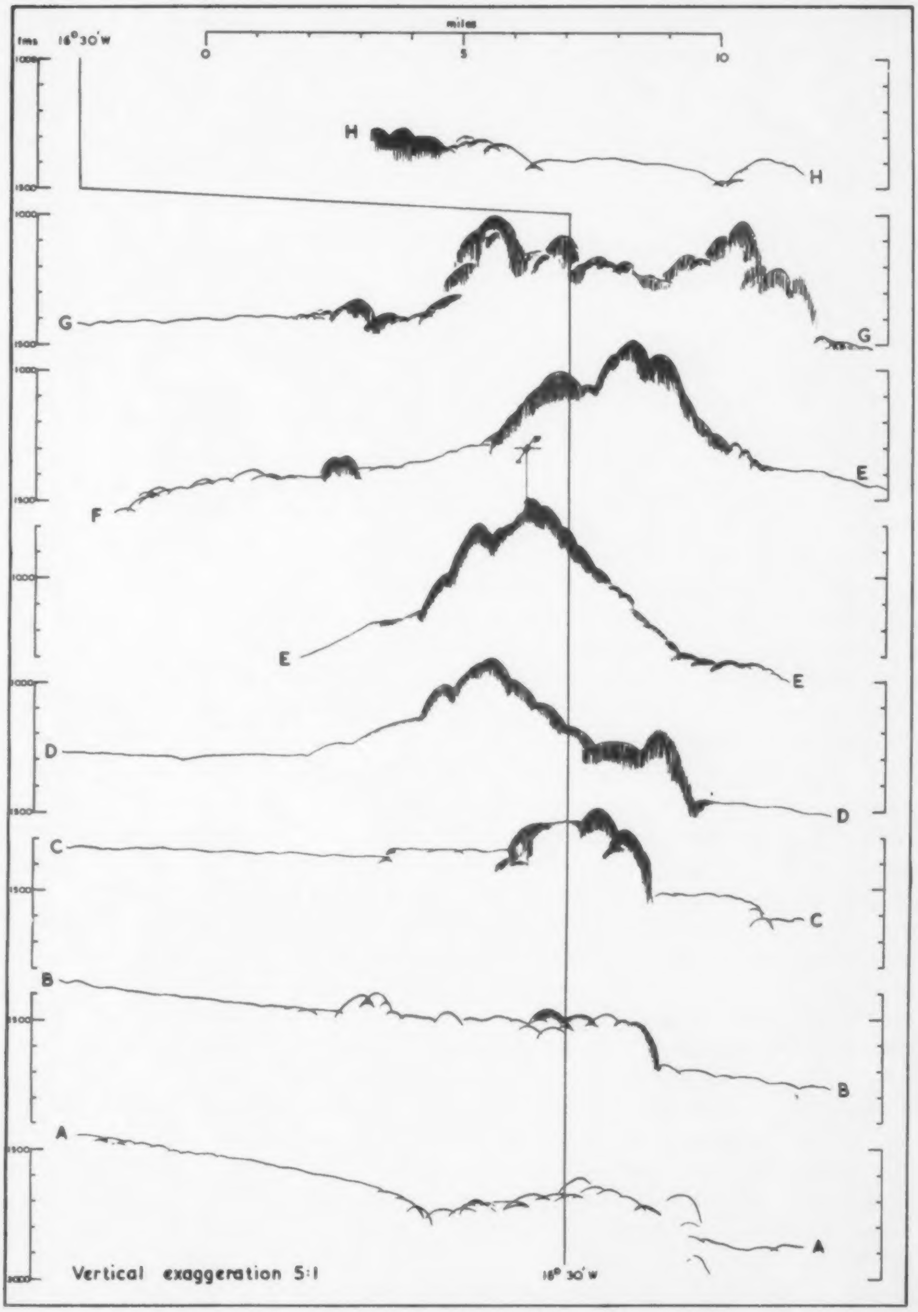


FIG. 4. Profiles of seamount showing characteristics of echo-sounding record.

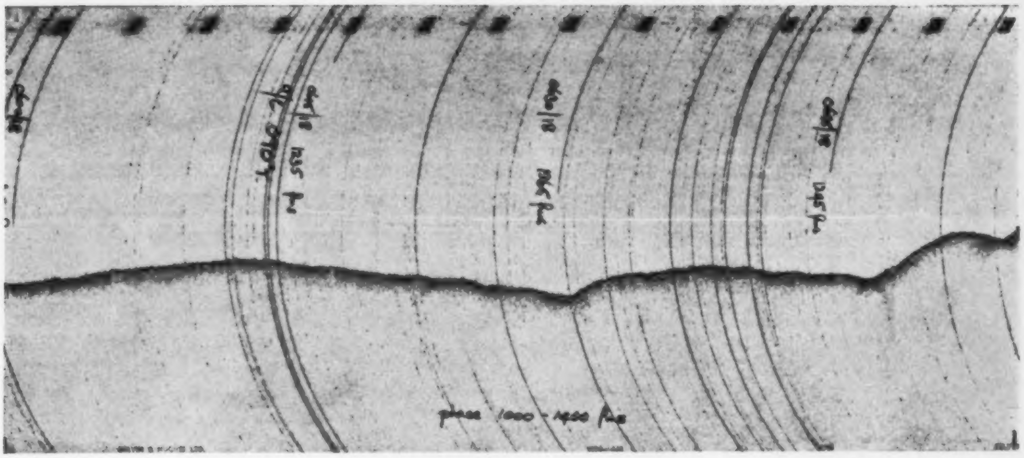
contour interval to illustrate the detailed topography in the region of two camera stations and three dredge stations (Fig. 3).

The contouring was carried out with continual examination of the echo-sounding records, to bring out, by the contour shapes, the peaks and valleys. In joining together adjacent profiles, a high degree of correlation of the main features was obtained. However, it was borne in mind that the usual dendritic patterns of subaerially eroded valleys are not necessarily found under the sea and that the valleys on the seamount may in fact just be depressions between two uplifted blocks and therefore without a downward trend.

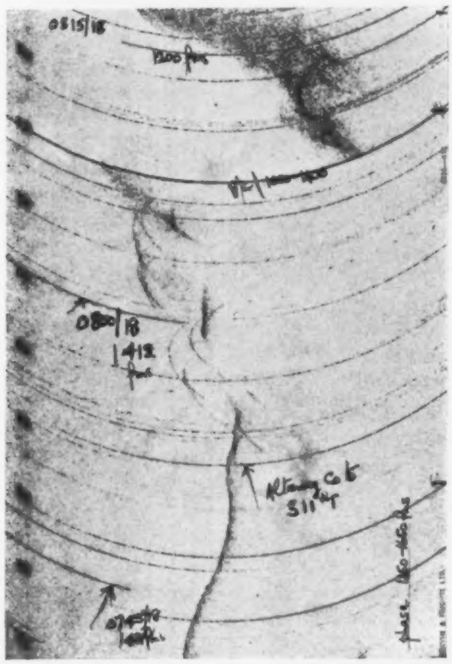
Profiles of the seamount at positions shown in Fig. 2 are illustrated in Fig. 4 with a vertical exaggeration of 5 : 1. These sections have been prepared from the echo-sounding records and reproduce the character of the bottom as seen by an echo-sounder beam of total width 16° to the half-power point and 40° to the first minimum. It will be seen that there are three characteristic types of echo, the single short echo, the multiple short echo and the long echo. Before discussing these types in detail it is instructive to consider the way in which these characteristics arise and how they can be interpreted to give us some information about the nature of the bottom.

The simplest type of bottom is flat and smooth. The term smooth is used here in the sense that the surface specularly reflects ultrasonic waves at 10 kc/s, which obey the laws of ray theory : a rough bottom acts as an area of secondary sources and can give non-specular reflections. The length of echo obtained from a flat smooth bottom, assuming no penetration, is the length of the transmitted signal. The length of echo obtained from a flat rough bottom with an echo sounder with effective beam angle of $2\theta°$ in a depth d is $d(\sec\theta - 1)$.

A single point reflector will give a hyperbolic trace on the record as the ship moves over it and the vertical range of the hyperbola will be $d(\sec\theta - 1)$. If the vertical exaggeration of the record is k, and x and y are the distance along and across the paper, then the equation of the hyperbola is $y^2 - k^2 x^2 = d^2$. Knowing the ship's speed and hence k, a hyperbola appearing on the record can be compared with the theoretical curve for a point reflector. If the observed curvature is less than the theoretical, then this indicates that the reflector is not in fact a single point but has a broad top. The length of an individual echo from such a feature is still, however, the outgoing signal length. In practice, the closest approximation to such a single point reflector, apart from midwater reflectors, is an isolated peak, with slopes greater than θ. Two cases can be distinguished here. If the peak is smooth in the sense discussed above, the echo will be short and the hyperbola will be a thin line, whereas if the peak is rough and echoes can be obtained from its side, they will be long and drawn-out due to the range of depths within the beam, and the hyperbola will be filled in. In areas where there are such filled-in hyperbolae on the record, we can obtain some information about the slopes that exist by considering the range of depths Δd from which echoes have been obtained and the diameter of the area ($2d\tan\theta$) examined by the beam. The minimum slope is given by $\tan^{-1}(\Delta d/2d\tan\theta)$ which assumes that the deepest and shallowest echoes have been obtained from diametrically opposite points of the area. A more probable slope persisting for a distance of $d\tan\theta$ is given by $\tan^{-1}(\Delta d/d\tan\theta)$.

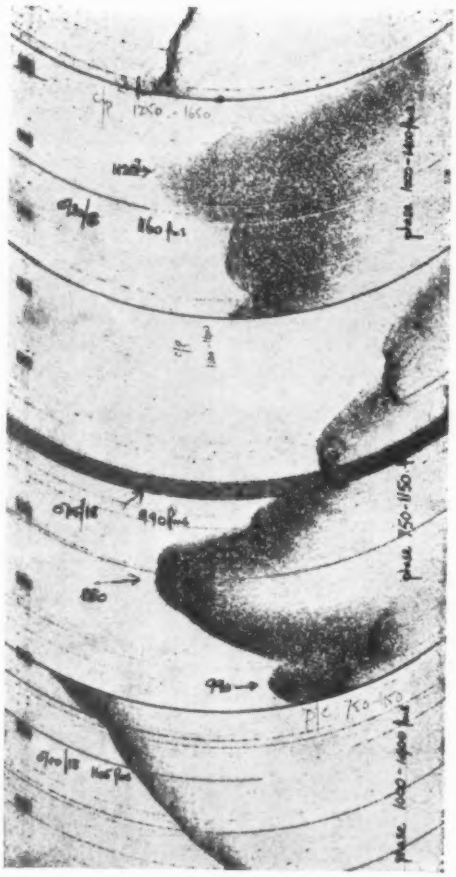


(a)



(b)

FIG. 5. Sections of echo-sounding record showing three characteristic types of bottom echo.



(c)

FIG. 5.

The three types of bottom echo observed in the seamount survey can now be discussed with reference to the above features. Typical sections of the echo-sounding record illustrating these types are shown in Fig. 5. The most straightforward case

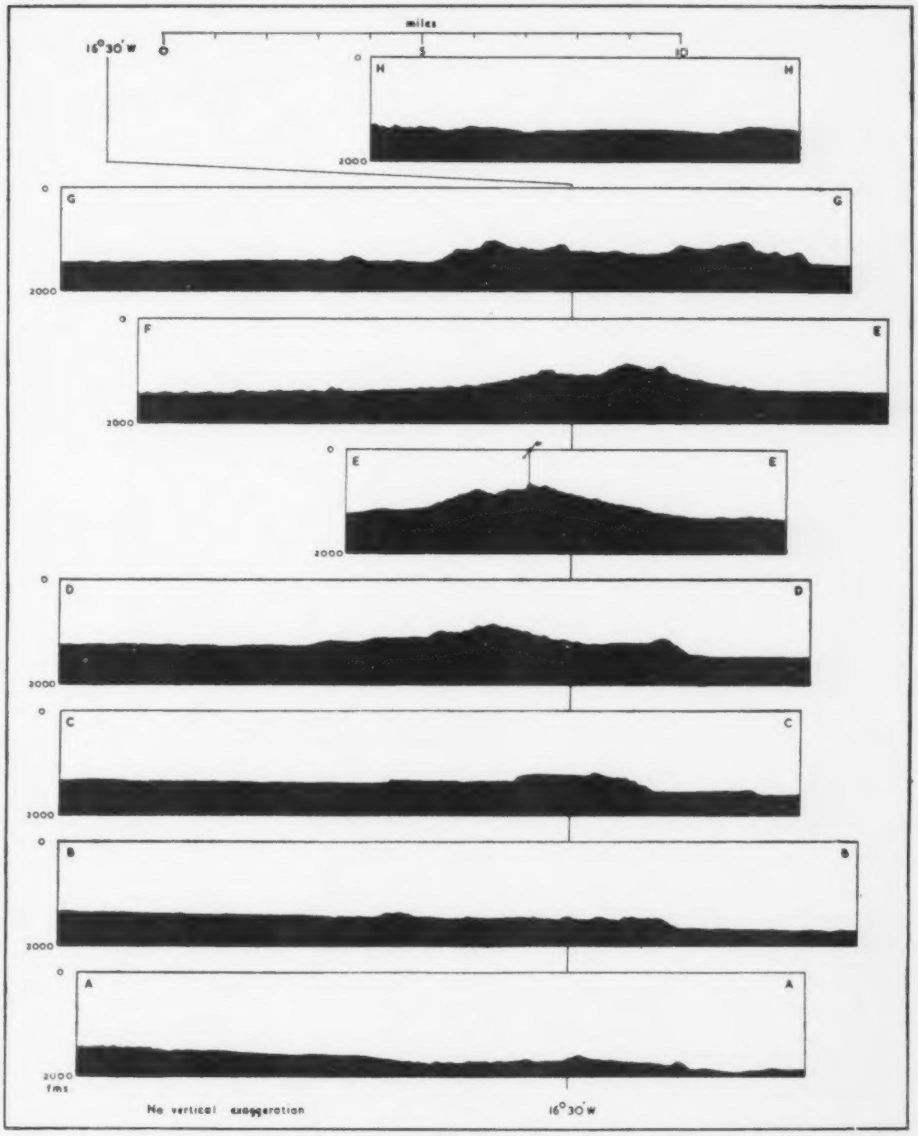


FIG. 6. Profiles of seamount reduced to natural scale interpreting the echo-sounding record in terms of real topography.

is the gently undulating or flat bottom where there are no multiple echoes and where the slopes are small compared to θ. In Fig. 5 (a), the depth is 1250 fathoms and the echo length is 20 fathoms. Photographs and coring show that this type of bottom

consists of sediments and that there is no small-scale relief capable of producing depth variations of 20 fathoms within the beam width. We must therefore assume that the bottom is acoustically rough and the effective beam necessary to produce this echo length has a 10° half angle.

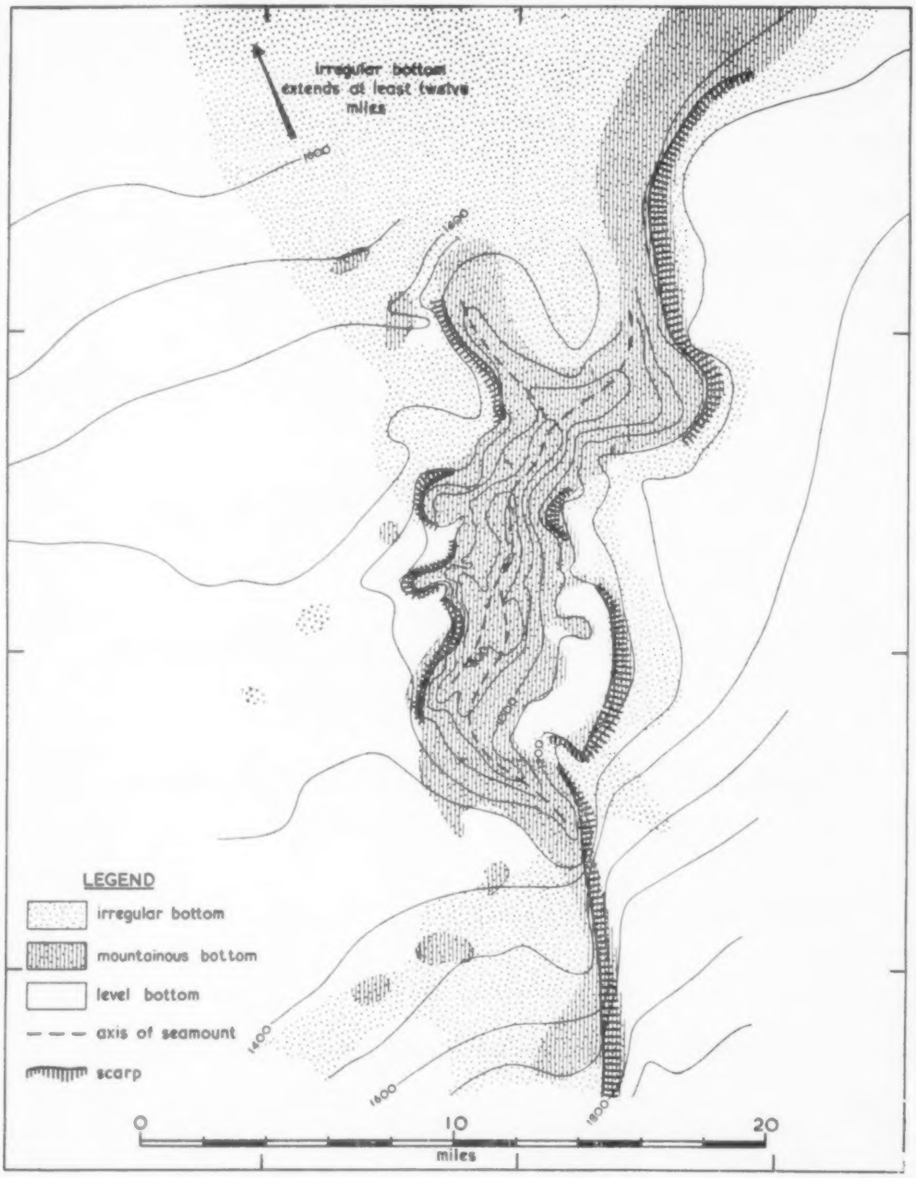


FIG. 7. Physiographic provinces and outstanding features.

The centre section of Fig. 5 (b) illustrates an area where there are multiple echoes produced from a succession of reflectors. The curves in most cases are somewhat

broader than the theoretical hyperbolae indicating a broad top to the reflectors. However, the length of the echo is about 2 fathoms which corresponds to the length of the outgoing signal, and this indicates that the reflector is smooth. We may then interpret these reflections as having come from broad rounded rocks with sides steeper than 10°. At 0800/18, there is a reflection from a flat bottomed valley between these rocks having the character of a rough sediment. Elsewhere between peaks the valleys have no infilling sediment and are V-shaped. If, as later evidence will show, the seamount is volcanic, then it may be that this irregular bottom is a more or less continuous field of submarine pillow lavas. The horizontal separation of the peaks is about 400 fathoms which gives a minimum height of 35 fathoms above the valleys.

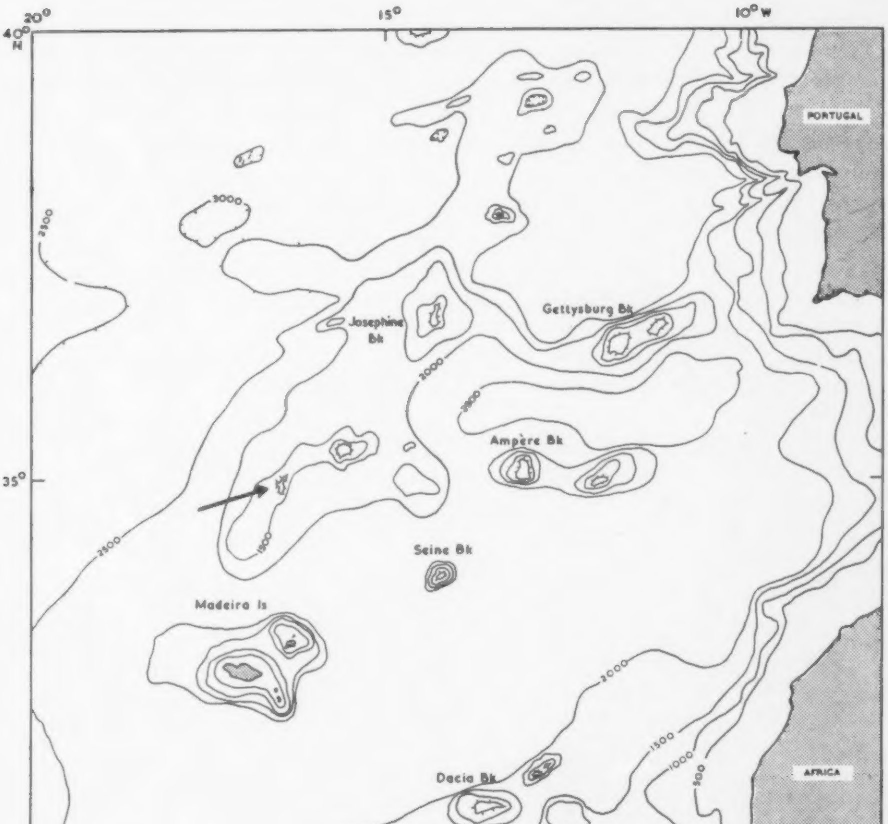


FIG. 8. Location of seamount in relation to neighbouring banks (contour interval 500 fathoms).

The third characteristic bottom-type was found in the central part of the seamount and is shown in the centre section of Fig. 5 (c). The mountainous nature of the bottom profile is combined with an echo length of about 100 fathoms. Analysis of this record shows that some of the curves are hyperbolae appropriate to their depth

indicating single-point reflectors. These are found on the side cliffs. Near the top the curves are broader and indicate wide peaks. The length of the echo shows that the bottom is acoustically rough and that within the area of the beam, slopes of at least 30° must persist for distances of 180 fathoms. Photographs of the bottom, and dredge hauls taken in these mountainous regions show that the surface is in many places covered with large boulders sitting in soft sediment. Such a bottom would provide a suitable acoustically rough surface. The main peaks are separated by about 1000 fathoms. Another possible explanation of the echo length is that the sound waves reverberate between reflecting surfaces before returning to the surface.

In Fig. 6 the sections of the seamount have been drawn to natural scale, to represent a true profile of the sea floor based on the above interpretations of the echo-sounding records.

The whole of the areas surveyed could be divided up into regions where the bottom fell into one of the three categories discussed above. These regions are shown in a physiographic chart (Fig. 7). In many places the regions follow the contours but in some places there is no correlation. The region of irregular bottom south of the seamount is bounded to the east by a mountainous scarp and to the west it disappears into the level bottom. The extent of this region to the south is not known. North of the seamount, the irregular bottom is similarly bounded to the east by a scarp and to the west by a level bottom, but to the north-north-west it extends for at least twelve miles where it was observed on another echo-sounding profile.

An important feature is the north-south scarp that defines the eastern edge of the seamount. This shows clearly on profiles AA, BB, CC and DD and extends far beyond the central mountainous region. The mean slope from top to bottom of the scarp is at least 20° in most profiles. Scarps have been indicated in the physiographic chart where cliffs of 20° or more are adjacent on their lower side to a comparatively flat area. Thus the scarp is absent on the eastern end of profiles FF and EE.

Another pronounced feature is a terrace of 1140 fathoms 4 miles south-east of the dan buoy bounded on the eastern side by the scarp. The surface of this terrace appears to be unconsolidated sediment.

The seamount is located on the crest of a gentle rise (Fig. 8) whose axis lies in the direction NE–SW, whereas the axis of the seamount lies N–S with an extension of irregular bottom to the NNW. On the same ridge fifty miles to the NE lies another seamount rising to 300 fathoms. This does not appear to elongated and is considerably bigger. (This seamount was the subject of several days investigation in 1954 by R.V. *Vema* of the Lamont Geological Observatory, New York). The elongation of the seamount described here is unusual and is not found in any of the other seamounts of this region.

EXAMINATION OF DREDGED MATERIAL

Three dredge hauls were made in the positions shown in Fig. 3, and the results listed in Table I. Station 3457 was planned following the examination of a photograph of Station 3452 (frame No. 9) which showed pronounced striations in the loose boulders on the bottom (Laughton 1957). Many of these were recovered and the striations proved to be corrugations on the surface of basaltic rocks due to layers of varying vesicularity, probably formed by successive flows of cooling lava.

All three dredge hauls include samples of basalt, which is clearly the main rock *in situ* on the seamount. Examination of thin sections has shown a medium to fine grained olivine basalt, with a variable but usually considerable content of glass. The olivine is mostly marginally altered, in places to reddish-brown iddingsite, but there are unaltered cores. In one sample an olivine nodule has a composition near Fo_{88}. Clino-pyroxene is present in prismatic crystals, tinged reddish, with hour-glass structure, angle $Z_v c$ about 45° and moderate 2V. The plagioclose is medium to basic labradorite. Glass, often enclosing dendritic iron-ores, forms part of the groundmass and a partial lining in some of the vesicles; it is variable in colour in thin sections from almost colourless to yellow-brown.

Table 1. *Dredge hauls*

Station 3451	Large flattened boulder of banded vesicular basalt (31 × 16 × 7 cm). Smaller cobbles of similar rock.
Station 3454	Three rounded cobbles of pumice (5 cm). One rounded cobble of microcline-granite (10 cm). One flattened slab of lightly-cemented foraminiferal aggregate. Eight various fragments of tuffaceous sediment.
Station 3457	One large rounded boulder of banded vesicular olivine basalt (25 × 25 × 15cm) and a number of smaller ones. Some of the smaller are also noticeably banded with more or less vesicular layers as in 3451. Most of these have at least a thin manganiferous black crust; on some a crust up to 2 mm thick is only discontinuously present, though the remainder of the surface is a weathered one with barnacles etc. One fragment of basaltic breccia (9 × 5 × 3 cm).

Near the original external surfaces, many of the vesicles are filled with opaque white material, to give an amygdaloidal appearance, but in all cases examined this proves to be merely a calcareous foraminiferal mud washed in from outside.

The external surfaces of most specimens of basalt are coated, patchily in places but more continuously in others, with a black manganese crust reaching a maximum thickness of 2·0 mm. Analysis of the crust has shown it to contain 19·2 per cent of iron, 17·1 per cent of manganese and 1·06 per cent of titanium. The manganese content is similar to that found in nodules in the Pacific (DIETZ 1955) but the iron content is somewhat higher.

One cobble from station 3454 is a fossiliferous tuffaceous mud petrographically related to the basalts. It is a composite sediment containing lithic, crystal and vitric components in addition to the calcareous foraminiferal matrix. There are small fragments of basalt, crystals of clinopyroxene and abundant isotropic yellow-red vitreous material which might loosely be described as a palagonite. It has, however, a refractive index near 1·590, higher than other recorded cases, and appears to be nearer to a sideromelane which has as yet suffered very little hydration towards a true palagonite.

Other cobbles from station 3454 are of a highly vesicular pumice, being wholly vitreous with a refractive index of 1·51 suggesting a trachytic glass. This identification is supported by one sample which contains a few phenocrysts of twinned sanidine and a greenish clinopyroxene. The high vesicularity of these pumices would enable them to float for many days and so they may not be locally

derived. Petrographically this appears to be identical with the recent pumice found drifting in the Pacific Ocean from Isla San Benedicto, which has been described by RICHARDS (1958).

One cobble has been identified as a coarse microcline-granite with small amounts of chloritised biotite. It is 10 × 8 × 6 cm and is well-rounded. It is the only specimen of a continental type of rock found in this region. DARWIN (1844) has described fragments of ejected granite rock associated with volcanic tuffs on Ascension Island and it is possible that the above sample may have been derived in this way. However, such ejected fragments are very rare and it is more likely, in view of the roundedness of the cobble that it has been ice rafted from the north. More recent dredge hauls elsewhere suggest that ice rafted erratic rocks are quite common in the north Atlantic.

BOTTOM PHOTOGRAPH

Photographs were taken of the bottom at three stations (Figs. 2 and 3) using a self-contained and automatic deep-sea camera (LAUGHTON 1957). In each case, the station was within radar range of the dan buoy and the drift during the station

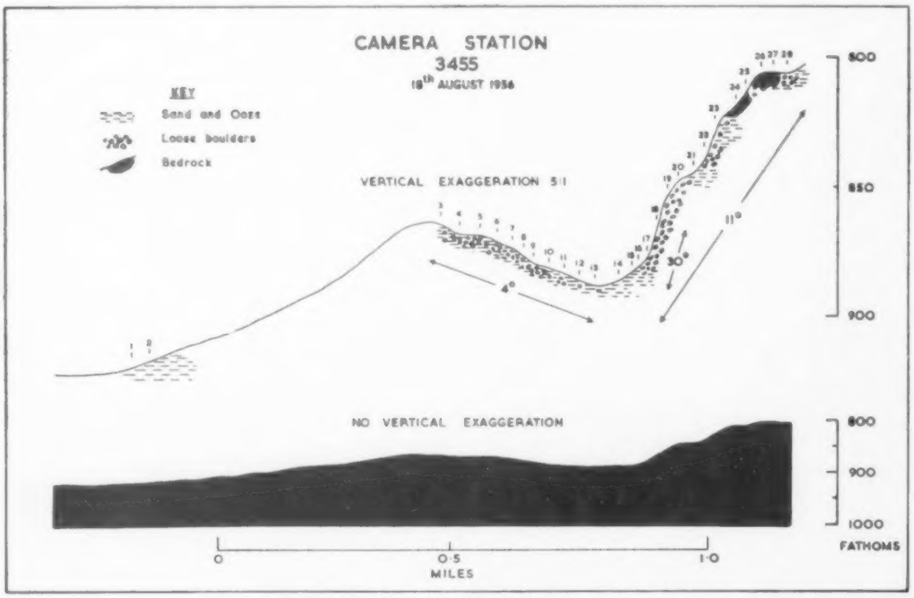


FIG. 10. Profile of sea floor at camera station 3455.

was accurately measured. In stations 3452 and 3456 the drift was negligible, but in station 3455 a drift of 1·3 miles enabled a series of pictures to be taken up the side of the seamount. In all photographs, the camera was 10·5 ft above the bottom, and looking at an angle of 50° from the vertical. If the bottom is horizontal, then the field of view on the centre diameters is 11 × 14 ft. However, when the bottom is sloping towards or away from the camera, the field is altered and the dimensions have to be guessed using a reasonable value of slope judged from the perspective.

Table 2. Frame 4*.

Table 2. Frame 5*.

FIG. 9. Sea bottom photographs at station 3452 (for full description see Table 2).

Table 2. Frame 6*.

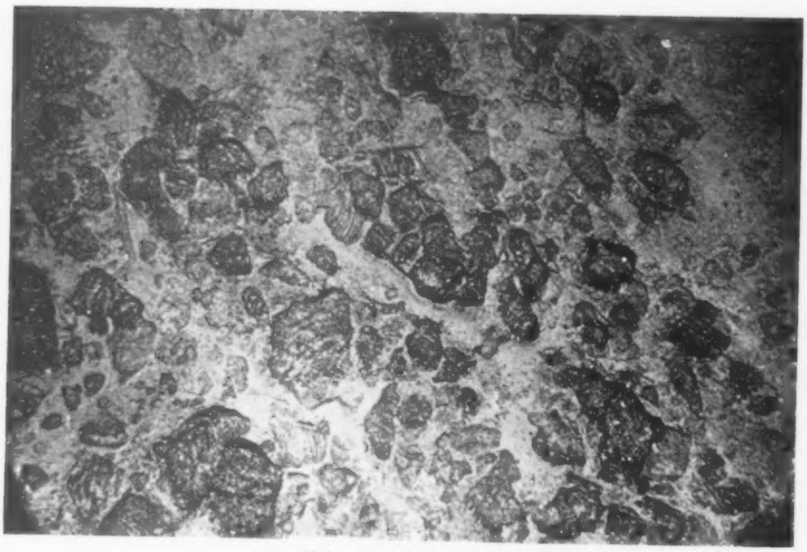


Table 2. Frame 9*.

FIG. 9.

Table 3. Frame 1*.

Table 3. Frame 10*.

FIG. 11. Sea bottom photographs at station 3455 (for full description see Table 3).

Table 3. Frame 11*.

Table 3. Frame 12*.

Fig. 11.

Table 3. Frame 15*.

Table 3. Frame 16*.

FIG. 11.

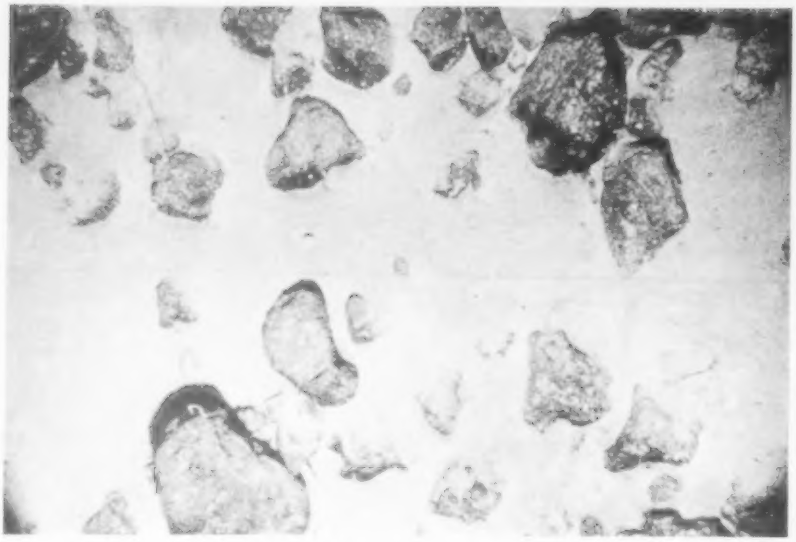


Table 3. Frame 18*.

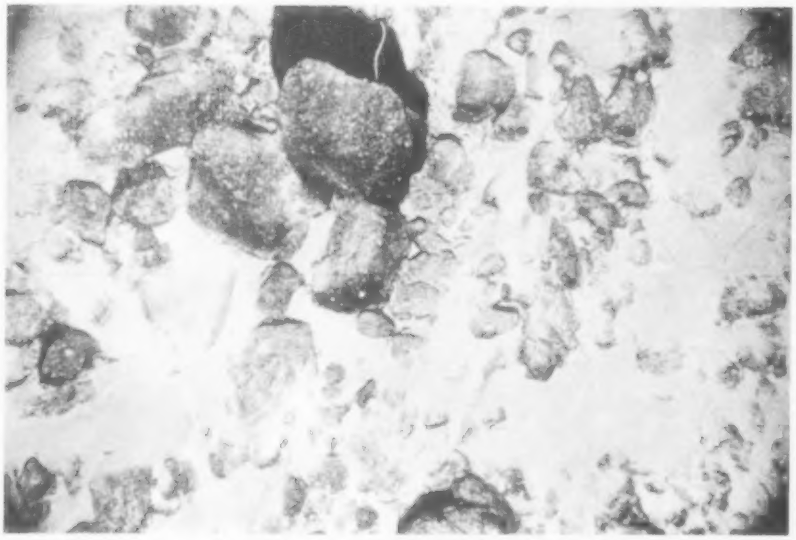


Table 3. Frame 19*.

FIG. 11.

Table 3. Frame 23*.

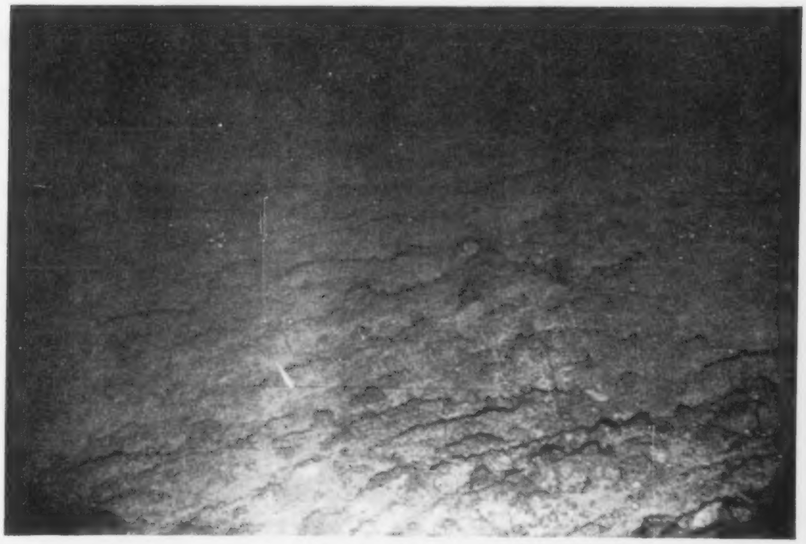


Table 3. Frame 25*.

FIG. 11.

Table 3. Frame 26*.

Table 3. Frame 27*.

Fig. 11.

Photographs at station 3452 are described in Table 2 and illustrated in Fig. 9. This station shows the gradation from flat sediments to loose boulders and solid rock near the top of the seamount.

Table 2. *Camera Station* 3452

Frame	*Wire out (fms)*	*Description*
2	806	Almost continuous field of dark shingle-size material overlying light coloured globigerina ooze. This material may consist of numerous shell fragments.
3	805	As in 2. The bottom also appears to be strewn with the spicules of sea urchins.
4*	804	The junction of two regions of sediment type. In the far left is normal globigerina ooze and in the near right organic debris as described in 2 and 3. In the transition zone are many loose cobbles and large spicules.
5*	801	Downslope view of massive rounded bedrock devoid of sediment, suggesting a submarine lava flow. A spiralling gorgonid and two hydroids are attached to the rock.
6*	797	Many loose cobbles, rounded and some striated, lying in a matrix of ooze.
7	792	Very dim downhill view of loose cobbles in ooze.
8	786	Very dim downhill view of loose cobbles in ooze.
9*	781	View into slope showing boulders and cobbles lying in a bed of ooze and sand. Many rocks show pronounced straight and curved striations with alternating dark and light bands. Currents are indicated by scour pockets around rocks. Several fragments of broken coral lie around.

*Illustrated in Fig. 9.

Station 3455 was planned to run along the track of the dredge station 3454, although in fact they did not coincide. After two pictures, the camera developed trouble and had to be recovered before continuing the profile. The rest of the pictures form a continuous sequence over a range of nearly 100 fathoms, crossing a small valley and then climbing up the seamount to a shoulder near the top (Fig. 10). The maximum slope calculated from the change of bottoming depth with the camera and the change of position, is 30° near the base of the main cliff. The pictures are described in Table 3 and illustrated in Fig. 11. A correlation between the topography and the nature of the bottom is evident. In the valley, the bottom is sediment-covered and very flat. On the slopes, the sediments have been swept clear by currents revealing boulders and cobbles. On the shoulder, both sediment and boulders are absent and only bedrock and consolidated volcanic tuffs are apparent. The boulder-covered slopes of the sides of the seamount would account for the acoustical roughness discussed earlier.

As a contrast, station 3456 was made on the smooth sediment-covered areas of the general rise on which the seamount is located. Table 4 describes the pictures, which are illustrated in Fig. 12. The pictures show a very flat surface without the

Table 3. Camera Station 3455

Frame	*Wire out (fms)*	*Description*
1*	991	Panoramic view downslope showing unconsolidated sediment in the foreground bounded by a low cliff (about 3 ft high) below which is a plain with long-crested ripple marks. Along the cliff edge are about 10 sea fans.
2	988	View into slope of flat featureless ooze.
4	870	Subangular boulders and cobbles almost buried by ooze on a slope. Many sea whips.
5	870	Cobbles half buried by ooze.
6	872	Cobbles and boulders and possible bedrock with ooze. A long coral spirals up from a rock footing.
7	874	Cobbles in ooze.
8	879	Cobbles in ooze with scour marks due to currents, and tracks in the ooze.
9	881	Cobbles in ooze with scour marks. Many sea whips.
10*	882	Mainly flat sediment with many tracks made both by surface and subsurface fauna. A few groups of cobbles have scour marks and sand drifts associated with them.
11*	885	Cobbles, scour marks and ooze on a slope.
12*	887	Single boulder with deep scour pit sitting on very flat sediment. The sediment is covered with small white patches as if produced by animals bringing lighter coloured subsurface sediment onto the top.
13	889	Flat sediment plain as in 12, with two cylindrical sponges with radiating conical root bundles (*Pheronema* ?)
14	886	Flat sediment overlain with patches of dark shingle-size material (possibly of organic origin). Dark ellipsoid-shaped object in background may be a holothurian.
15*	880	Sediment and shingle criss-crossed with tracks and possibly current-produced ripple marks.
16*	875	Very rounded boulders lying in ooze showing pronounced scour and sand drifting. There are several small tracks in the sediment.
18*	865	View into slope showing boulders up to 2 ft diameter lying in ooze. The boulders are rounded, pitted and appear to have typical managanese crust.
19*	853	View into slope showing boulders up to 2 ft diameter lying in ooze. The boulders are rounded, pitted and appear to have typical manganese crust.
20	848	View into slope showing boulders up to 2 ft diameter lying in ooze. The boulders are rounded, pitted and appear to have typical manganese crust.
21	845	Sediment speckled with small black spots.
22	839	Cobbles lying in ooze and shingle. Gorgonid.
23*	828	Cobbles lying in crusted and ridged sediment. Spiralling gorgonid.

Table 3—contd.

Frame	*Wire out (fms)*	*Description*
24	819	Crusted sediment with few small cobbles and small spherical sponges (?)
25*	813	Panoramic view of rough rugged terrain with the appearance of crusted volcanic ash in ridges.
26*	806	Bedrock outcropping through cemented volcanic conglomerate with very little sediment cover. An accumulation of spicules suggests current action. The fauna have been tentatively identified as follows : Chrysogorgid possibly *Isis* (top right); a Zeid fish possibly *Neocyttus* (middle right); a large Gorgonid or Antipatharian (top centre); a spiralling Gorgonid related to *Iridogorgia* (lower centre); sea anemones scattered in the rock.
27*	806	Bedrock, crusted volcanic conglomerate, boulders and cobbles without sediment cover. Spiralling Gorgonid in centre (cf. 26).
28	806	Angular cobbles scattered on ooze and shingle with white patches as in 12.

*Illustrated in Fig. 11.

degree of reworking that is found on the abyssal plains and in deeper water. This may be explained by a greater rate of sedimentation due to the relative lack of solution of calcium carbonate in 1200 fathoms, increased productivity in the surface waters due to upwelling caused by an obstruction or to the sediment that would have been deposited on the seamount, being swept to the flanks by currents.

All three processes may contribute to a high rate of sedimentation. The shallow mounds of lighter sediment must be attributed to extensive burrowing and subsequent smoothing action by currents.

MAGNETIC SURVEY

The investigation of the seamount included measurements of the total magnetic intensity by means of a towed nuclear spin magnetometer. This instrument had been developed for work at sea by the Department of Geodesy and Geophysics, Cambridge, and was first used during the expedition. A description of the instrument has already been published (Hill 1959). The observed field values were corrected for diurnal variation and heading effect, and removal of the regional field as follows :—

(*i*) *Diurnal variation.* The overall accuracy of a survey at sea is reduced by the uncertainty in determining the diurnal variation of the Earth's field. For this survey, the hourly values of the field at two observatories were used. These were San Miguel in the Azores, approximately 450 miles to the north-west and Coimbra in Portugal, approximately 500 miles to the north-east. Since the diurnal variation is a solar phenomenon, any correction to the observed field values derived from hourly values at an observatory must be related to the longitude of the observatory relative to the ship's longitude.

For two days during the survey, a plot of hourly departures from the mean field over the six week period of the expedition, calculated from hourly readings, is shown for San Miguel and Coimbra (Fig. 13). In order to compare the variations more easily, the San Miguel results have been shifted

Table 4. *Camera Station* 3456

Frame	*Depth (fms)*	*Description*
1	1240	Flat ooze with broad dark patches and occasion a small white mounds. Several tracks can be seen and a burrow which is typical of all those found in this station. Instead of being circular, it consists of two mounds on opposite sides of a hole. Its origin is unknown.
2	1240	Flat patchy ooze with small spherical sponges of 1 in. diameter (*Tethya* ?), tracks and a semi-circle of small mounds.
3*	1240	Flat patchy ooze with burrows as in 1, sponges and a holothurian (12 in.).
4*	1240	Flat patchy ooze as above but with an area of about 20 sq. ft. of shallow mounds containing many burrows. This area is lighter in colour than the rest of the bottom and appears to behave more like a loose sand.
5	1240	Flat patchy ooze with white spots.
6	1240	Flat patchy ooze with white spots, burrows and sponges.
7	1240	Flat patchy ooze with spots and small holothurian (?).
8*	1240	Flat patchy ooze with burrows as in 1, rows of small mounds and tracks.
9*	1240	Flat patchy ooze with mounds, burrows and tracks. Six dark objects are possibly small holothurians.
10	1240	Flat patchy ooze with burrows as in 1.
11	1240	Flat patchy ooze with burrows as in 1.
12	1240	Flat patchy ooze with burrows as in 1.
13	1240	Flat patchy ooze with burrows, sponges and holothurian (?).
14	1240	Flat patchy ooze with burrows as in 1.
15	1240	Flat patchy ooze with burrows as in 1.
16	1240	Flat patchy ooze with area of shallow mounds and burrows as in 4.
17	1240	Flat patchy ooze with burrows as in 1.
18	1240	Flat patchy ooze with sponges, tracks (one being made by a Limule or 'King Crab') and a fish (2 ft long).
19	1240	Flat patchy ooze with burrows, tracks and small holothurians.
20	1240	Flat patchy ooze with burrows and tracks
21	1240	Flat patchy ooze with burrows, shallow mounds, holothurian and fish (18 in.).
22	1240	Flat patchy ooze with burrows as in 1, white spots and small holothurian.

*Illustrated in Fig. 12.

Table 4. Frame 3*.

Table 4. Frame 4*.

FIG. 12. Sea bottom photographs at station 3456 (for full description see Table 4).

Table 4. Frame 8*.

Table 4. Frame 9*.

FIG. 12.

by 1 hour 9 minutes so as to make the local mean times at the observatories the same.

Fig. 13 shows quite clearly that the amplitude of the variation at Coimbra is much larger than that at San Miguel. For two days of the survey, the 17th and 18th August, the noon departures for Coimbra are $-53\,\gamma$ and

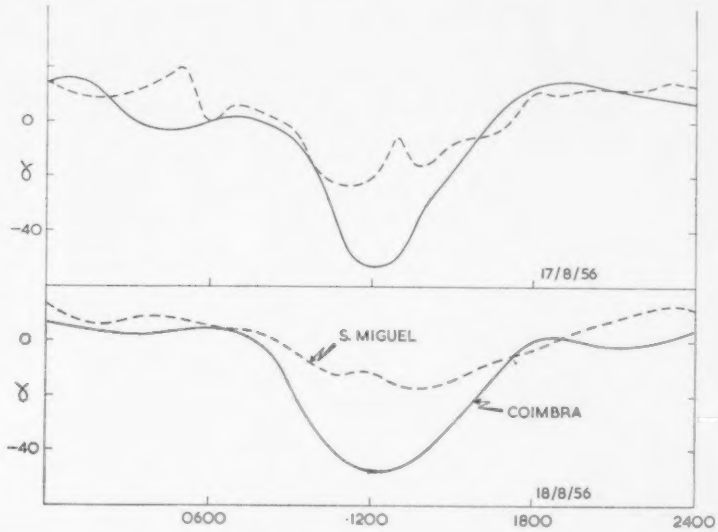


FIG. 13. The diurnal variation recorded at the observatories of San Miguel (Azores) and Coimbra (Portugal) for the two days 17th and 18th August 1956.

$-46\,\gamma$ respectively, while those for San Miguel are $-21\,\gamma$ and $-11\,\gamma$ ($1\,\gamma = 10^{-5}$ oersted). Since Coimbra is less than 3° north of San Miguel, such large differences in noon departures could not be accounted for by the difference in latitude. Clearly the correction, derived from the mean of those noon values, may be something like $\pm 15\,\gamma$ in error. However, practically the whole of the survey was carried out at night when diurnal variation is very much reduced and the probable error is $\pm 5\,\gamma$.

(*ii*) *Heading effect.* A correction also had to be applied for the effect of the ship's magnetism which will vary with the heading of the ship. (This effect was reduced to negligible proportions on subsequent expeditions by increasing the distance between the magnetometer and the ship). From experiments carried out at sea around an anchored buoy, the effect of the ship on different headings has been calculated and used in the reduction of all magnetic data. The heading correction is of the order of $\pm 10\,\gamma$.

The estimated total error of a single observation is $\pm 10\,\gamma$.

(*iii*) *Removal of the regional field.* The anomalous values in the total field were calculated by removing a regional field with a linear gradient. The gradient was derived from world charts of the total magnetic intensity (U.S. Coast and Geodetic Survey 1955). The regional field was taken to be :

$$F = 42{,}000 + 7{\cdot}94\,\mathrm{N} - 0{\cdot}85\,\mathrm{E}$$

where N = minutes of latitude north of the point 34° 37′N, 16° 30′W

E = minutes of longitude east of the point

and F = is in gammas.

The magnetic field in the neighbourhood of the seamount was found to be most irregular. The most striking feature is the NE–SW direction of the contours which is the same direction as the general trend of the topography of the area (Fig. 14). This tendency for magnetic contours to follow structural trends is one that has been observed in many subsequent surveys at sea.

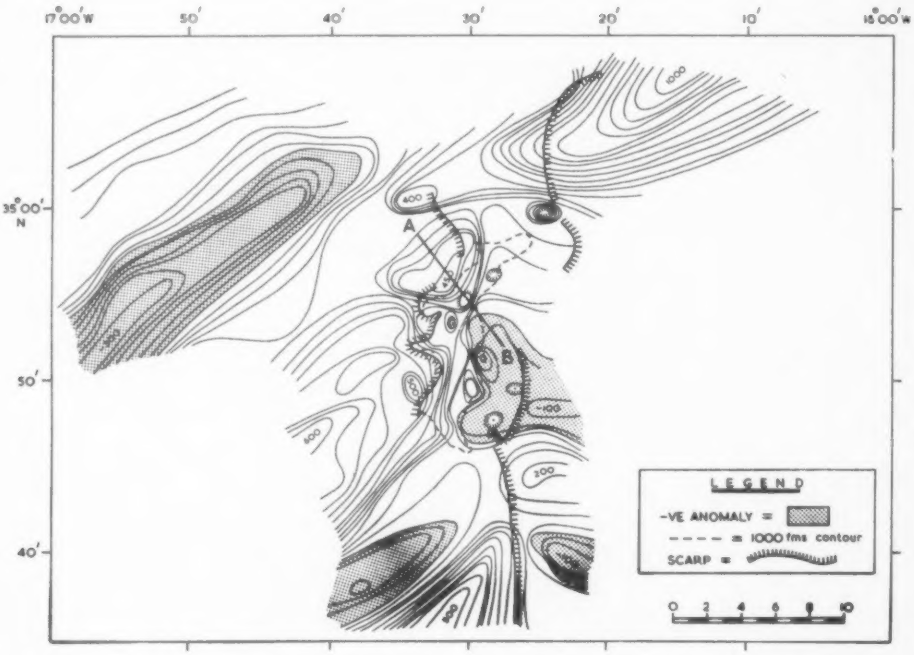


FIG. 14. The magnetic contour map of the area showing the anomalies in total field, after removal of regional gradient (contour interval 50 γ). (A)–(B) = section shown in Fig. 16.

The largest anomaly (in the north-east of the map) was recorded on the track away from the area after the main survey had been completed. Although a scarp cuts across part of the anomaly, the highest field values were recorded on a track which sloped gently from 1350 fathoms in the west, to 1550 fathoms in the east.

A second feature of the map is the erratic nature of the contours and the local magnetic ‘highs’ and ‘lows’ around the bank.

Fig. 15 (a) shows the observed anomaly along Section AB with the topography plotted below (vertical exaggeration 2 to 1). The shape of the seamount can be approximated to a trapezoid with a flat top at 800 fathoms and sloping down to a depth of 1500 fathoms on either side. The anomaly due to such a shape was calculated,

assuming that the rock was characterized by an intensity of remanent magnetization so much greater than the intensity of induced magnetization that the latter could be neglected. It will be shown later that this is a reasonable assumption in view of the measurements made on four boulders dredged from the area.

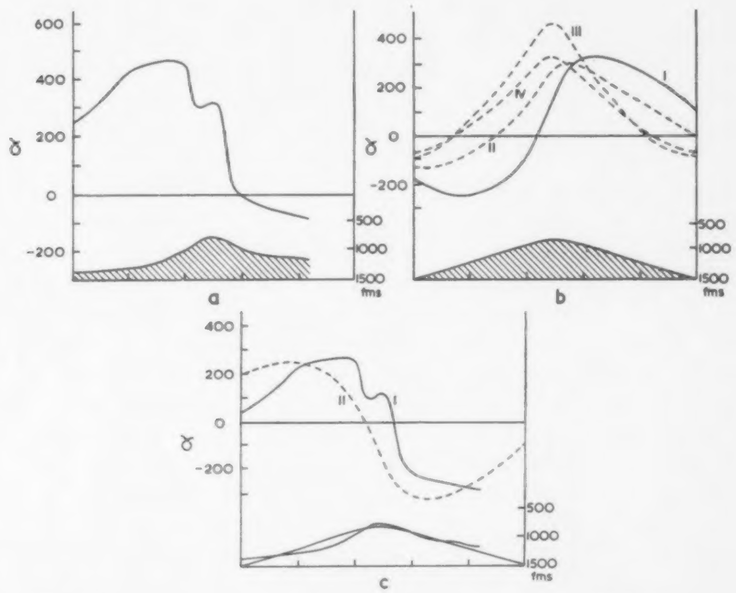


FIG. 15. (a) The observed magnetic anomaly over the seamount. (b) The calculated curves for the trapezoid for $I = 52°$ but with the horizontal component of remanent magnetisation in four different azimuths (i) 13½ °W of N (in direction of the present earth's field) (ii) 13½ °N of E (iii) 13½ °E of S (iv) 13½ °S of W. (c) (i) The observed anomaly with the zero increased by 140 γ. (ii) The calculated curve for the trapezoid with reversed polarity. The seamount and trapezoid are shown superimposed.

However, if we allow that remanent magnetization alone will produce the anomaly we cannot be certain that the direction of the magnetization will be the same as the present direction of the Earth's field. Fig. 15 (b) shows the calculated anomalies produced by the trapezoid for four directions of the horizontal remanent magnetization. The inclination in each case was assumed to the be same as the present inclination, i.e. 52°, while the intensity of remanent magnetization was taken to be the same as that of the dredged material, i.e. $5 \cdot 0 \times 10^{-3}$ gauss.

Now if we call k_{app} the apparent susceptibility, F the present total magnetic intensity (0·42 oersted) and I_R the intensity of magnetization, then

$$k_{app} F = I_R$$
$$= 5 \cdot 0 \times 10^{-3}$$

Therefore $k_{app} = 1 \cdot 2 \times 10^{-2}$ c.g.s. units.

The method of calculating the anomaly produced by a trapezoid was described by PRESS and EWING in 1952. The above value of k was used in the calculations.

Now since this method assumed that the trapezoid extends to infinity in both directions and also since the trapezoid is only an approximation to the shape of the seamount, an exact fit between the observed and calculated curves could not be expected. However, the errors should not be too great, and a qualitative agreement, at least, might be expected.

Comparison of Fig. 15 (a) and 15 (b) show that none of the computed curves could be made to fit the observed anomaly. In fact, the dissimilarity was so striking that a curve was computed assuming reversed polarity in the structure, that is, with the assumption that during the formation of the rock, the magnetic north pole was in the position of the present magnetic south pole. The results are plotted in Fig. 15 (c).

In order to match the curves, the ' zero ' of the observed curve had to be increased by 140 γ. The ratio of maximum to minimum anomaly is then approximately the same for both curves. Changing the values of the assumed intensity of remanent magnetization could not change this ratio. That the value of the regional field might be 140 γ higher than that originally chosen is not altogether unlikely since the linear gradient was derived from the map of total magnetic intensity of the U.S. Coast and Geodetic Survey which may be subject to large inaccuracies over the oceans. There will also be an error in extrapolating the regional field from world maps to such a small area as that of the survey. (A linear gradient was removed in preference to a gradient based on a least squares reduction of the observed data since the latter process suffers from the disadvantage that significant magnetic trends due to deep structures may be removed).

The evidence for a reversed polarity is far from complete. Many interpretations are possible. A body of different shape and higher apparent susceptibility at a greater depth may cause the anomaly and the observed negative anomaly may not be associated with the positive anomaly that has been taken in the interpretation. However, *if* the anomaly is due to a body of the same approximate shape as the bank and with the same intensity of remanent magnetization as the dredged material, then the observed anomaly favours reversed, rather than normal, polarity in the rock.

Physical measurements of dredged material from station 3457.

(*i*) *Density.* Five small cylinders were cut from four boulders of vesicular olivine basalt (described in Table I). The apparent density was found from direct measurements of the weight and volume of the cylinders. The true density was calculated by crushing the rock to a powder and weighing the powder in a specific gravity bottle filled up with water. (Table 5).

Table 5

Specimen	*Apparent density*	*Assumed true density*	*Vesicularity*
A	1·85 gm/c^3	2·82 gm/c^3	34%
B	1·61 gm/c^3	2·82 gm/c^3	43%
C	1·68 gm/c^3	2·82 gm/c^3	40%
D1	1·76 gm/c^3	2·82 gm/c^3	38%
D2	1·77 gm/c^3	2·82 gm/c^3	37%

(*ii*) *Vesicularity.* The differences in the values of apparent density of the five specimens were considered to be due to varying degrees of vesicularity. On this assumption, the vesicularity has been calculated for each specimen by comparing density with an assumed true density of 2·82 gm/c³. The results are shown in Table 5. Specimen D1 and D2 were cut from the same boulder.

(*iii*) *Magnetic properties.* The remanent magnetism of the rock specimens was measured by a method which depends on the deflections of an astatic magnetometer (BLACKETT 1952). To measure the intensity of the remanent magnetism the field at the centre of the system is made zero by adjusting the current in a set of Helmholtz coils. Deflections are measured with the specimen offset to the East and West of the vertical axis of the suspension system. Readings are taken for four orientations of the cylindrical specimen in an upright position and four orientations with the specimen inverted. Thus sixteen measurements in all are made on one specimen.

It was originally intended to measure the magnetic susceptibility by repeating the experiment described above with the vertical coil off. In this way the specimen acquires a magnetization induced by the vertical component of the Earth's field. However, for the five specimens under consideration, it was found that the strength of remanent magnetization was much greater than the induced magnetization which meant that the increase in the deflection produced by the induced magnetization was small compared with the deflection produced by the remanent magnetization. In such a case, the determination of susceptibility is not likely to be very accurate. Consequently, the susceptibilities were measured on an Inductance Bridge. The ' off-balance ' produced by a rock specimen was compared with that produced by a cylinder of ferric chloride crystals whose susceptibility was accurately known. The results are shown in Table 6. It should be noted that the susceptibilities quoted refer to the highly vesicular rock. The susceptibility of the powdered rock will be higher by a factor True Density/Apparent Density.

Table 6

Specimen	*Intensity of remanent magnetism (gauss)*	*Susceptibility (c.g.s. units)*
A	$5·0 \times 10^{-3}$	$2·9 \times 10^{-4}$
B	$5·1 \times 10^{-3}$	$4·3 \times 10^{-4}$
C	$4·8 \times 10^{-3}$	$2·8 \times 10^{-4}$
D1	$4·8 \times 10^{-3}$	$4·0 \times 10^{-4}$
D2	$5·3 \times 10^{-3}$	$3·7 \times 10^{-4}$

Seismic station 3453

A line of seismic refraction shooting was undertaken across the seamount using the sono-radio buoy technique described by HILL (1952). Two buoys were attached to the dan buoy moored on the top of the seamount and shots were fired along the line shown in Fig. 2. The depth profile and shot positions along this line are shown in Fig. 16. The corrected depth beneath the buoys was 780 fathoms and the depths at the shot points varied from 1135 fathoms to 1320 fathoms. The depth of the hydrophones was 200 feet and the shot depth 250 feet.

Because of the comparatively large variations in depth along the line of shots, considerable corrections have to be applied to the times of arrival. These have been made assuming parallel layering. On this assumption the corrected time distance diagram appears as in Fig. 17. The low velocity line on this diagram indicates a compressional wave velocity of 3·7 km/sec, its intercept on the time axis, assuming a

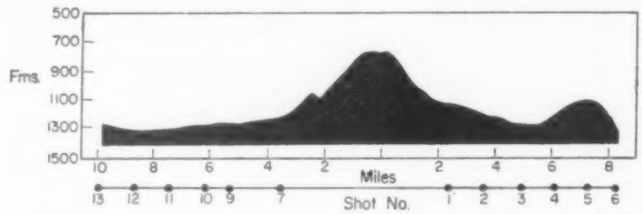


FIG. 16. Profile across the seamount along which the shots were fired. The scales show (a) the distance in miles from the sono-radio buoys and (b) the shot positions. The vertical exaggeration is 5 : 1.

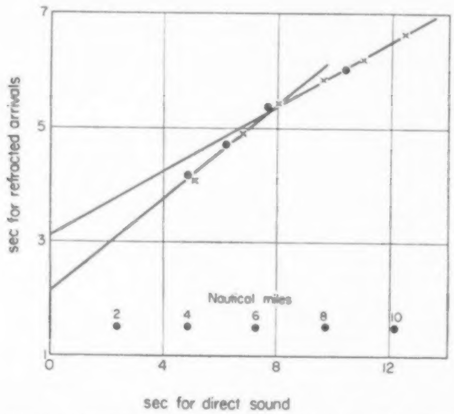


FIG. 17. The Time-Distance diagram of the refracted arrivals. The crosses indicate the arrivals from the shots to the south of the buoys.

surface layer velocity of 2 km/sec, gives a thickness of 450 m, (250 fm). The higher velocity line is poorly established, but suggests a slope equivalent to approximately 5·3 km/sec. The intercept on the time axis is equivalent to a thickness of the layer with velocity 3·7 km/sec of 2200 m, (1200 fm).

The assumption of parallel layering is perhaps not the most plausible; the steep flanks of the seamount and the photographs make it unlikely that 450 m of unconsolidated sediments exist on the top. If this layer is thinned near the top, then it must be thickened on the flanks. If this thickening increases steadily with increasing depth, then it will have the effect of giving a lower apparent value of the velocity in the layer below than in fact exists. On the other hand the positions of the shots nearest to the buoys are well down from the peak and uniformity of thickness of the layer along the line of the shots is therefore not unreasonable, even if the layer is absent under the sono-radio buoys. It is clear from the time-distance diagram that there is symmetry in layering on the two sides of the seamount.

This result must be compared with similar measurements on two seamounts on the mid-Atlantic ridge. The details of these two stations are as follows :

Station No.	Position of Buoys	Depth under Buoys	Length of Line	Direction
Cr 42	46° 43′N 27° 09′W	1000 fms	7 miles	330°
Dy 28	46° 23′N 27° 12′W	840 fms	8 miles	025°

Station Cr 42 has been described by GASKELL, HILL and SWALLOW (1958) and the second by HILL (1959). In the first the superficial rocks did not provide compressional waves but it was concluded that the velocity of compressional waves must lie between the limits 2·5 km/sec and 3·8 km/sec. Assuming the higher limit this layer was 100 m in thickness; with the lower it was 600 m. Below this rock with unknown characteristics was a layer with velocity approximately 5·7 km/sec. No depths or velocities were obtained from any layer below this.

The second station showed that any superficial unconsolidated layer would be less than 130 m in thickness and that below this layer, if it existed, there was a layer of thickness 1200 m and velocity 3·6 km/sec overlying a further layer of indeterminate thickness but with velocity of 6·4 km/sec.

The following is a summary of the three seamount results :

Station No.	Depth of Peak, (fms)	Velocity in first Rock Layer, (km/sec)	Thickness of first Rock Layer, (m)	Velocity in Rock Layer, (km/sec)
Cr 42	1000	2·5–3·8	600–1100	5·7
Dy 28	840	3·6	1200	6·4
Discovery 3453	780	3·7	2200	5·3

Further comparisons can be made with the results of EWING and EWING (1959) of seismic stations on the mid-Atlantic ridge when they found the upper rock layer (equivalent to the second rock layer here) to have a mean velocity of 5·15 km/sec. However if only the best reversed stations are chosen (E3, E4, E5 and E6) the velocities of this layer are given by 5·60, 5·83, 5·71 and 5·80 km/sec respectively. This layer was interpreted as basaltic volcanic rock. Only in stations E5 and E6 is a semiconsolidated layer found with velocities of 1·94 and 2·79 km/sec respectively. The 5·7 km/sec layer agrees well with the second rock layer of the three seamounts discussed above, although a 3·5 km/sec layer was not found.

In view of the uncertainties of measurement, these results are reasonably consistent with one another and suggest that the seamounts of the north east Atlantic consist of a layer of relatively low velocity lavas overlying a volcanic ‘ core ’ of considerably higher velocity at a depth below sea level which is above that of the seafloor in neighbouring oceanic areas. This ‘ core ’ is not composed of rock (Layer 3) such as would be found immediately above the oceanic Mohorovicic Discontinuity since the velocity is too low; likewise it is near the high limit for the layer (Layer 2) sandwiched between the unconsolidated sediments and Layer 3, although it is possible that it can be classed with this layer. It seems more probable that these volcanoes produced rock types not normally found in the crust of the deep ocean floor.

DISCUSSION

The feature described in this paper rises 600 fathoms above the level of the top of the rise, and thus qualifies to be called a seamount. However its elongation in a north-south direction and the extension of irregularities on the bottom suggest that it is part of a feature that might better be called a ridge. Dredging has shown that the exposed rocks are principally volcanic and this is confirmed by the magnetic anomalies associated with it and by the seismic velocities. The possibility that the magnetization of the rocks was acquired at a time when the earth's field was reversed, is plausible in the light of recent work on palaeomagnetism where there is strong evidence that reversals in the earth's dipole field have occurred often throughout geological time (IRVING 1959). However, reversals have been observed as recently as the Pleistocene and so it is not possible to use this evidence as a means of dating the seamount.

The magnetic anomalies do not, however, extend over the whole length of the feature, suggesting that the volcanism is a second effect following what appears to be a fault over 50 miles long running approximately north-south; that is, at 45° to the general trend of the rise linking this to the seamount to the north east. The scarp zone, and the general lower level of the sea floor to the east of the seamount imply either a downward displacement of the eastern side of the fault of about 200 fathoms or a northern movement of at least four miles. The grouping of seamounts in this region and the belt of earthquake epicentres which goes through it (HEEZEN *et al.*, 1959, Plate 29) show it to be an area that is still tectonically active, being possibly connected with the active region of the mid-Atlantic ridge.

It has been thought worthwhile by the authors to describe in some detail the features of this seamount, not so much because an immediate interpretation can be put on them but because few seamounts in the Atlantic have been closely studied. Only by analysing other seamounts in a similar way can comparisons be made and their true significance be appreciated.

Acknowledgements—Geophysical examinations of this sort can only be carried out with the co-operation of many scientists and seamen. The authors would especially like to thank Sir EDWARD BULLARD, who did much of the reduction of the magnetic data, and other members of the Department of Geodesy and Geophysics, Cambridge, who participated in the cruise. The rock samples were kindly examined by Dr. F. C. PHILLIPS of Bristol University.

None of the work could have been done without the assistance of the Master, officers and crew of R.R.S. *Discovery II*.

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INSTRUMENTAL NOTE

A Telemetering Hydrophone

WILLARD DOW

(*Received* 20 *July* 1960)

Abstract—This report describes a deep, telemetering hydrophone which transmits its information acoustically through the water to a surface vessel. The instrument has the advantage of requiring no electrical cable to the ship and, being self-contained, may be quickly hung on any suitable supporting line or wire. Alternatively, any type of inexpensive single-conductor cable of sufficient strength, such as oil-well logging cable, may be used to replace the acoustic link for some purposes if desired.

(1) INTRODUCTION

A TELEMETERING hydrophone has been developed for listening at great depths in the ocean. This device has the advantage that a multi-wire electrical cable incorporating a low-loss coaxial line is not required to connect the hydrophone to the receiving vessel or other listening post. Electrical cables of this nature having sufficient reinforcement to withstand the considerable strain involved, almost invariably have to be of special design and must be made to order at high cost. They are usually of such diameter and inflexibility as to make handling difficult without large winches and sheaves particularly designed for their use. The weight and bulk of such installations present severe problems particularly aboard small vessels where deck space is at a premium.

This deep hydrophone is capable of telemetering its information acoustically through the water to the receiving point from depths of 12,000 feet or more. The device is completely self-contained and may be quickly clamped to any wire or line capable of supporting 70 pounds.

Alternatively, for quiet operation at greater depths, any cheap single-conductor cable capable of withstanding the strain (such as $\frac{1}{4}$ in. oil well logging cable) may be used effectively to pipe the information to the surface, in spite of the high transmission loss and other undesirable electrical characteristics usually found in cable types which are not designed for wide-band transmission.

Performance

The first model of the Telemetering Hydrophone was constructed in 1954 and tested at sea (Fig. 1) in April, 1955 from R/V *Atlantis*. In spite of the low output power, about 1 watt, the device operated successfully using the acoustic link to a depth of 6,500 ft. However, battery life was short and the dynamic range was only about 10 db at maximum depth.

An improved model incorporating a built-in pulse generator for calibration purposes, a more efficient modulator and a 4-watt power output stage, was constructed in 1956, and battery life was extended to six hours. Signal-to-noise ratio ranged from 20 db at approximately 10,000 ft to 35 db at the surface. Broadband noise referred to the hydrophone preamplifier input (across the crystal) was 4 microvolts (μv) for a 5 kc bandwidth.

Transistorizing the deep unit in 1958 permitted an extension in battery life to 12 hours (before recharging), an increase in power output to 30 watts, a wider dynamic range (55 db) and a decided improvement in stability and reliability of the transmitter and its power supply. Other specifications are similar to those for the 1956 model.

The transistorized gear has already seen considerable sea duty at depths down to 18,000 ft using logging cable. It is expected that the acoustic link will also prove effective over a greater range than has been possible with the low powered units.

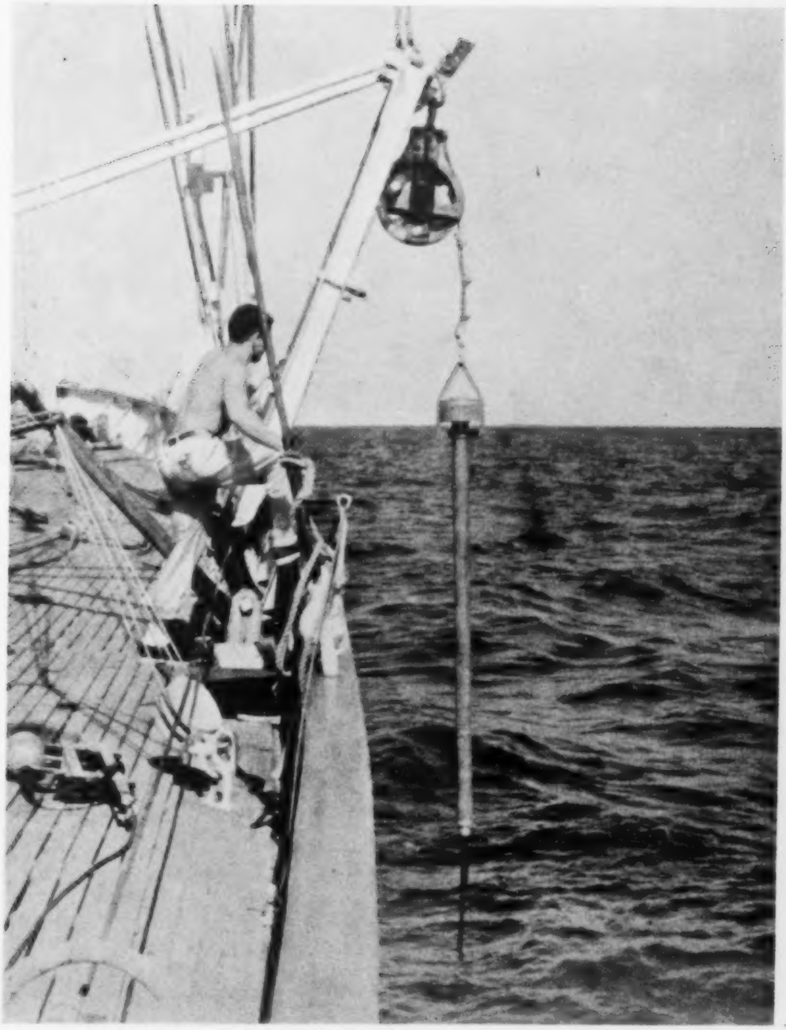

FIG. 1. Deep Transmitter ready for lowering from R/V *Atlantis* in April 1955 (Surface receiving hydrophone lies on deck at lower left of photograph).

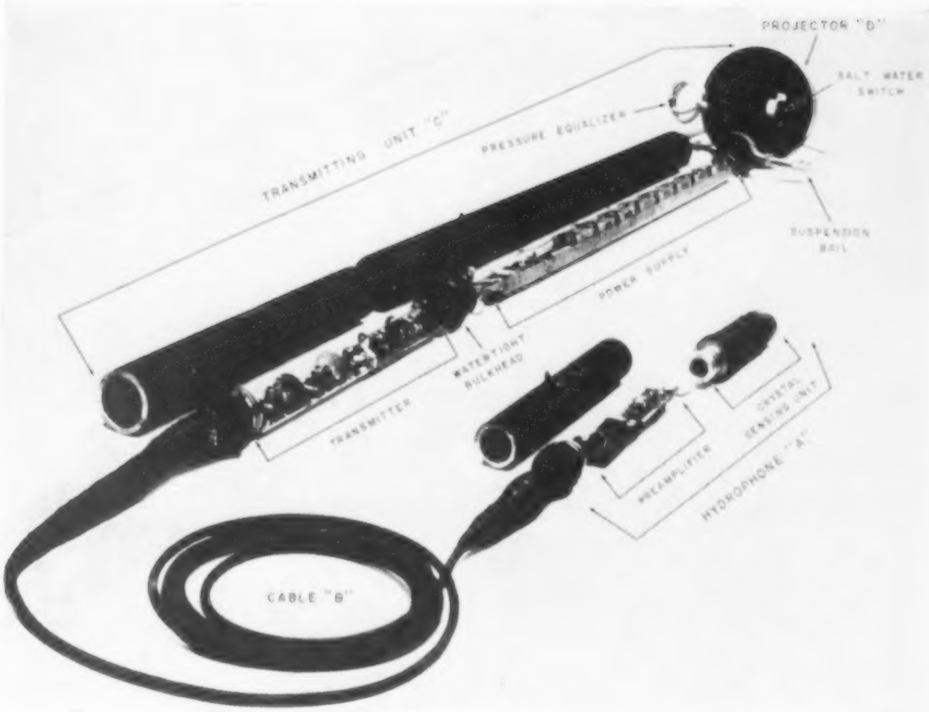

FIG. 3. Component assembly of Deep Gear.

(2) PLAN OF OPERATION

The plan of operation is shown in Fig. 2, and Fig. 3 pictures the deep gear assembly. A hydrophone (A) is suspended by a 40 ft electrical cable (B) from the bottom of the transmitting unit (C) which, in turn, is clamped to a trawl wire, nylon cord or other supporting line.

The hydrophone, together with its built-in preamplifier, has a frequency range of 50 cycles to 5 kc. Both omni-directional and line hydrophones having vertical directivity have been used.

The output signal from the hydrophone preamplifier is passed through the short cable to the transmitter where, after further amplification, it is applied as modulation to a 21 kc carrier. The modulated carrier is then amplified and used to drive a high-frequency projector (D) beamed vertically upward toward the ship.

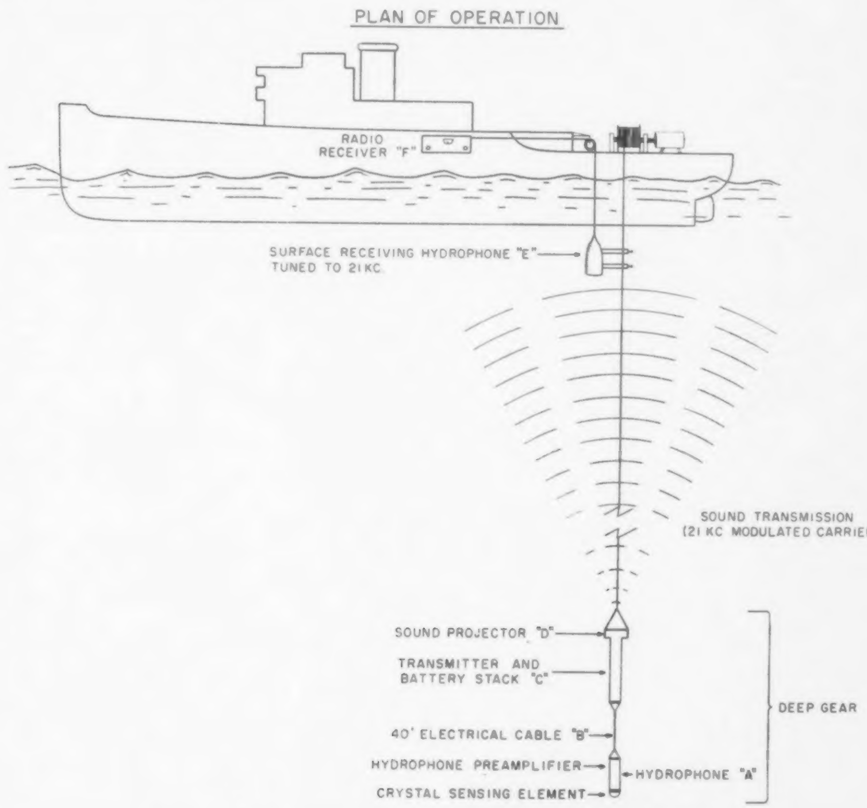

FIG. 2. Gear suspended from ship at sea in operating position.

When the transmitter has been lowered to a point about 10 ft above the desired depth, the surface receiving hydrophone (E) is clamped to the line which is then lowered the additional 10 ft or until the surface unit is completely immersed. This receiving hydrophone being beamed toward the deep transmitter is now in a position to receive the acoustic carrier. After passing through the hydrophone preamplifier, this carrier is transmitted through a short cable to a conventional low-frequency radio receiver (F) in the ship's laboratory where it is further amplified and then demodulated to recover the original intelligence. The highly-selectivity tuned radio frequency circuits in the hydrophone preamplifier and radio receiver effectively eliminate low-frequency ship and water noise, 60-cycle pickup and other interference outside the pass-band, which is centered at 21 kc. As a result, the system has remarkably low background noise from these sources, usually 60–80 db below maximum output.

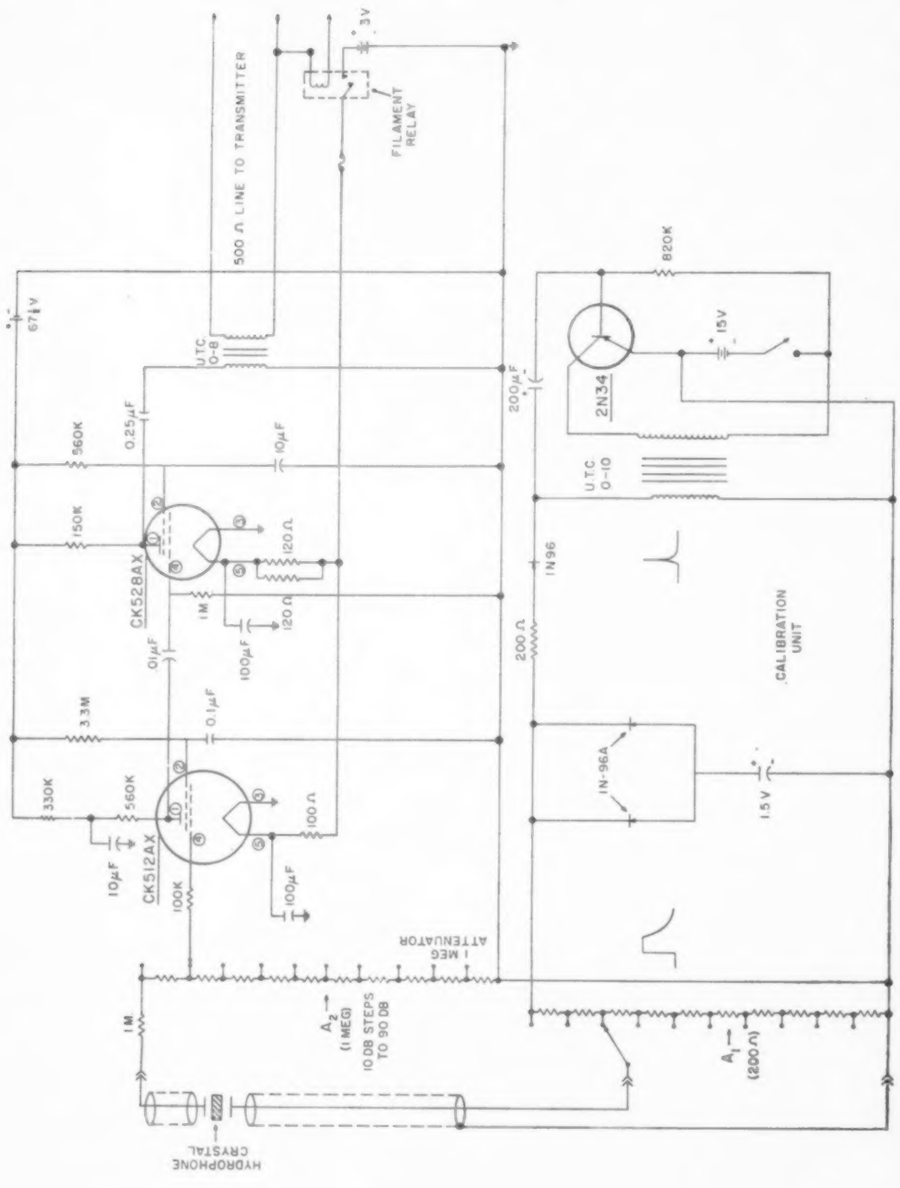

FIG. 4. Schematic Diagram of Deep Hydrophone Preamplifier (Vacuum Tube Version).

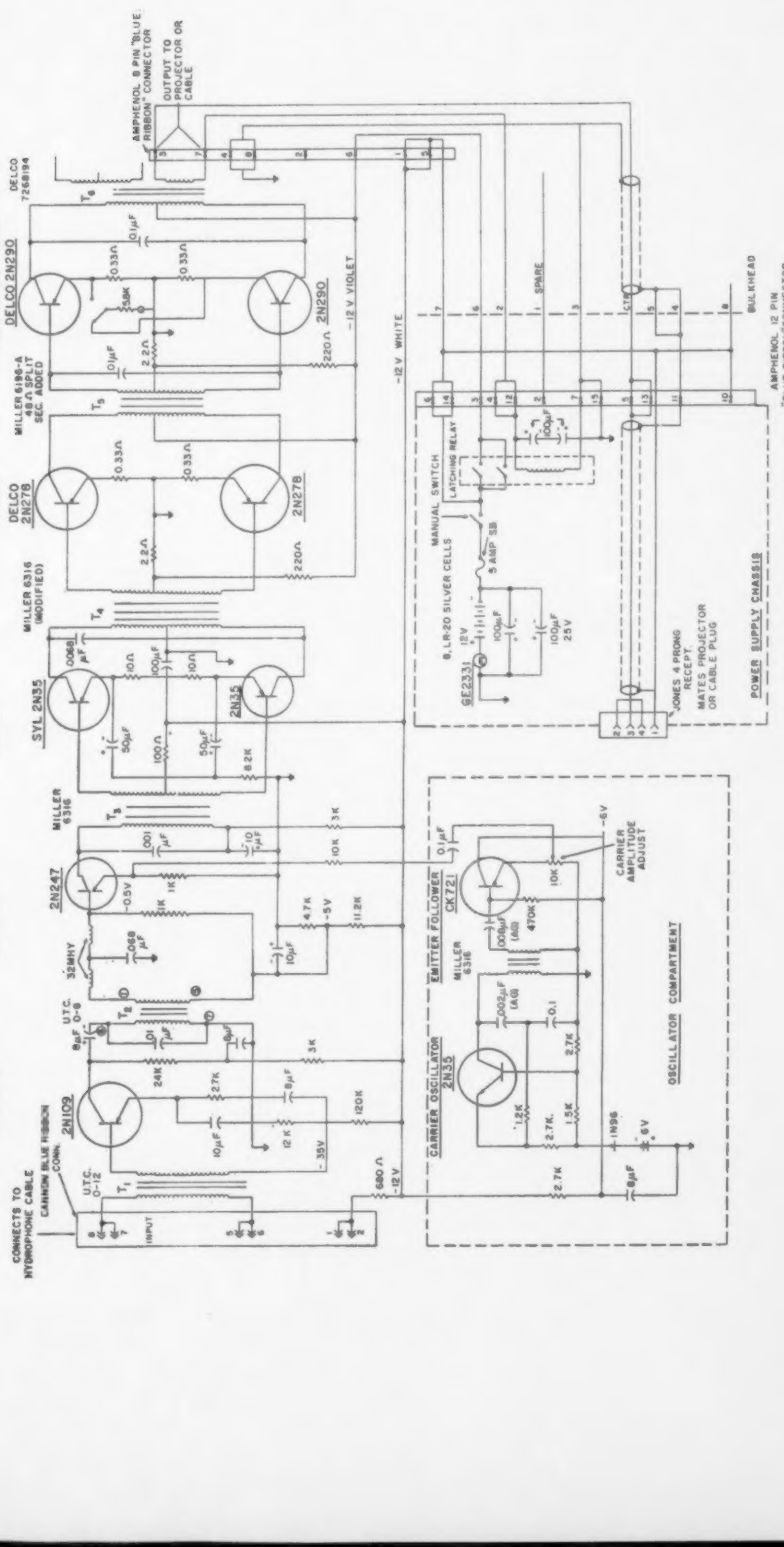

FIG. 5. Schematic diagram of Main Transmitting Unit.

Operation with logging cable is similar except that the carrier is transmitted directly from the deep transmitter to the radio receiver via the insulated centre conductor, sea water being used as the return. However, even this simple, small-diameter electrical cable together with its special slip-ring winch not only requires more careful maintenance at sea but does not offer the convenience and adaptability of the acoustic version as will be seen in the discussion of applications at the conclusion of this paper.

The design of the new equipment (Model 3) will now be discussed in detail.

(3) ELECTRONIC DESIGN

Fig. 4 is a schematic diagram of the hydrophone preamplifier. The Ammonium Dihydrogen Phosphate (ADP) crystal hydrophone responds to sounds in the deep ocean in the frequency range from 50 cycles to 5 kc. In series with the crystal element is a 200 ohm step attenuator (A1) across which is impressed a short calibration pulse every 8 seconds. This pulse, which is developed by a type 2N34 transistor pulse-generator, is rectified and clipped by type 1N96 diodes to maintain constant amplitude regardless of battery and temperature conditions.

The attenuator controls the voltage applied to the calibration resistor. Input attenuator (A2) controls the signal voltages applied to the input of the two-stage preamplifier. These attenuators are at present pre-adjusted for the operation desired by removing a pipe plug in the side of the preamplifier case. (A system for remote control of attentuation by signals from the surface is now under construction).

After passing through the preamplifier* the audio signal is transmitted through a short cable to the main transmitting unit (Figs. 5 and 6) where, after passing through an additional audio gain stage and a carrier trap in the form of a low pass filter, it is applied to the base circuit of the 2N247 type transistor modulator.

A 21 kc oscillator unit comprising a type 2N35 transistor oscillator and CK721 type transistor emitter-follower supplies carrier power to the emitter circuit of the modulator and the 21 kc modulated carrier appears across the primary of transformer T_3.

This carrier, after passing through two class-B, linear, driver-amplifier stages and a final power-stage, is applied through matching transformers (T_6) to the acoustic projector or electrical cable depending on the type of operation desired.

The 12-volt power-supply consists of eight 20 ampere-hour silver cells. The latching-relay circuit shown in the diagram is part of a remote-control system which permits the transmitter to be switched on and off in the ship's laboratory. Its function is primarily to conserve battery power between experiments when the gear is down or being lowered. At present it is operable only when the electrical cable is being used but an acoustically-triggered switch is being developed.

(4) STRUCTURAL DESIGN

The structural layout of the deep gear is shown in Fig. 3. The ADP crystal in the deep receiving hydrophone unit is mounted in an aluminium tube having large sound-windows. A flexible neoprene boot is stretched over this tube and the unit is filled with oil under low pressure and sealed.

The hydrophone preamplifier is contained in a two-inch diameter aluminium tube. The preamplifier compartment is separated from the crystal unit and hydrophone cable by watertight bulkheads containing sealed electrical feed-throughs. Similar bulkheads are used to separate the transmitter, power supply and projector compartments in the transmitting unit, so that if any one section should develop a leak others the will not be affected. The compartments are made watertight by double 0-ring sliding seals between the bulkhead units and the inside walls of the aluminium tubes. These tubes are shown lying beside the electronic chassis in Fig. 4. They are secured to the bulkheads with bolts. The internal chassis which contain the electronic assemblies plug into electrical connectors mounted on the bulkhead walls so that they may be easily extracted for service or to recharge batteries by removing either bulkhead.

The projector contains an ADP crystal assembly in an oil-filled aluminium case covered by a rubber sound-window. Since it is a conventional, shallow, sonar unit, its rear terminal seals are not designed to withstand the 10,000 lbs./sq. in. pressures that the telemetering gear is subjected to in the deep ocean. Therefore, these seals are backed up by a small oil-filled compartment mounted on

*The preamplifier shown is a vacuum tube component of the Model 2 equipment adapted for use with Model 3 pending completion of the new transistorized preamplifier shown in Fig. 7.

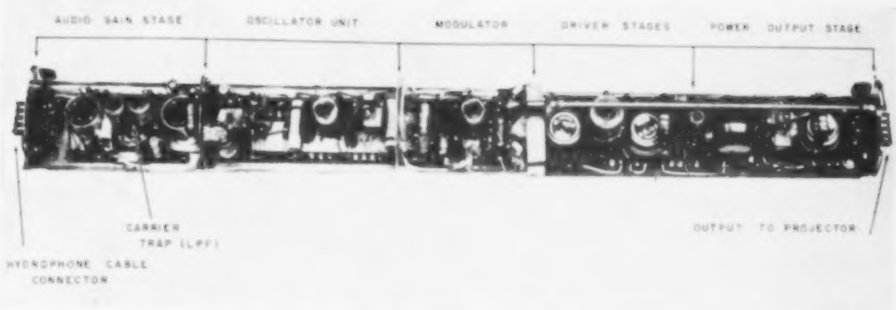

FIG. 6. Layout of Deep Transmitter Chassis.

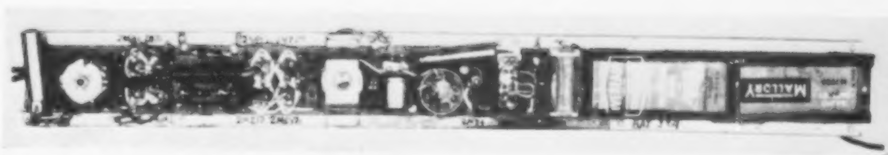

FIG. 7. Layout of Deep Hydrophone Preamplifier Chassis (transistor version).

the back of the projector housing (Fig. 3). The oil in this compartment is subjected to the same sea pressure as is presented to the crystal side of the projector rear wall so there is no pressure differential across the terminal seals. Sea pressure is transferred to the interior of the small compartment by means of a sealed, soft-rubber tube exposed to the ocean and filled with oil which is in communication with the oil in the compartment.

An insulated terminal mounted on the wall of the compartment is connected to a relay circuit in the battery stack. When the gear is immersed, the terminal is connected to ground (case) via the salt water path thereby energizing the relay and turning on the gear. This salt-water switch insures that the gear cannot accidentally be left operating on deck, precaution required not only to prevent battery discharge, but to protect the power transistors from the high, deck-temperatures of the tropics.

(5) APPLICATIONS

As pointed out in the introduction of this paper, the principal advantage of the acoustic-link system is that no electrical conductor is required to connect the receiving hydrophone to the ship or other listening post. It is also quite obvious that the deep instrument, being self-contained, can be made to operate completely free of the ship. This fact permits such developments as bottom-mounted or midwater-moored listening units capable of supplying information over high-frequency, acoustic-carrier links beamed toward ship or shore.

Acoustic-carrier telemetering of information from a towed " fish " has proved successful (Dow, 1954) and such a fish can readily be made to listen to sounds in the sea by building into it a transmitter similar to the one described here. There are numerous other applications. For example, the deep unit has been used to detect sounds reflected from sub-bottom strata. Heretofore bottom reflection studies in deep water have been carried out with hydrophones near the surface, and either shallow or deep sound sources. However, when the receiving hydrophone is close to the bottom the path of the reflected signal through the water becomes very short with the result that transmission losses are greatly reduced and masking from side reflection is eliminated.

The possibilities of using the gear in this way are presently being explored. LUSKIN *et al.* (1960) following a design similar to the one outlined here have recorded seismic refraction arrivals in deep water. At Woods Hole tests are being planned which will combine the instrument described above with a repetitive pulse source (The Edgerton Thumper) both submerged near the bottom in deep water.

Acknowledgements—The author wishes to thank the following for their contributions to the development of the instrument.

Dr. J. B. HERSEY conducted many acoustic tests at sea and provided valuable help and advice. He also assisted in the preparation of this paper. STEPHEN STILLMAN developed the final structural design of the various internal chassis in the deep gear, then fabricated and wired them. He also assisted materially with the acoustic tests at sea and in many other respects. LLOYD HOADLEY, SYDNEY KNOTT and WARREN WITZELL helped to design and build the original watertight cases for the deep gear as well as for the deep and surface hydrophones. ROY L. RATHER of the Commercial Engineering Corporation and several members of the staff at the Woods Hole Oceanographic Institution have provided valuable assistance with the equipment both in the laboratory and at sea.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

Contribution No. 1130 *of the Woods Hole Oceanographic Institution. This work was performed under Contract Nonr*-1367 *with the Office of Naval Research, U.S. Navy Department.*

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LETTER TO THE EDITORS

Internal waves on an echo sounder record

(*Received* 16 *June* 1960)

DURING the year 1957 (March to August) the R.V. *Baldaque da Silva* carried out an echo and trawl survey off the coast of Angola (Portugese West Africa). Some interesting echo traces were collected which had the character of a scattering layer, but a wave form was superimposed upon them.

The echo sounder was a standard 'Fishfinder' 649–11 made by Atlas Werke AG, Bremen; frequency 30 kc/s; pulse length, 1 ms; 112·5 transmissions per minute. The gain control was set at 5–6 (full gain being 10 arbitrary units). This gain was standardized to give a soft third echo from the bottom in 30 m; under these conditions no noise appeared on the paper. Most traces were recorded under way, but some were recorded on station or at anchor.

FIG. 1 shows a typical trace. In the upper waters (roughly the top 50 m), there is an intense scattering layer, consisting partly of small discrete traces, as if of small shoals, and partly of a diffuse and characterless trace. The marked wave pattern is seen in the lower half of the trace, at about the depth where a thermocline might be expected. In the deeper water, below the edge of the wave pattern, fish traces are recorded both in the mid-water (60–90 m) and on the bottom (in 100 m). The number of fish traces in the lower water column can be roughly associated with the thickness of the scattering layer. In certain traces it is interesting to report that intermittent noise records could be associated with the presence of killer whales (FIG. 2).

FIG. 3 shows the wave pattern very clearly and it will be seen that the traces in the wave are of single fish; this can be established by the fact that the received pulse length is constant during the recording. The majority of traces are of single fish, but some are a little thicker, showing that they may have been received from small fish shoals. Bathythermograph records show that the thermocline was at a very different position when the instrument was hauled upwards from that recorded on the way down. It is suggested that the wave pattern is caused by fish being moved in an internal wave.

The wave pattern shown in FIG. 4 is composed not of single fish traces but of diffuse layers which follow a sinusoidal course in depth. In the shallower part of it, fish traces are present, but in general it can be said that the traces are caused by layers of small organisms, rather than by groups of single fish or groups of small shoals of fish. In this case the internal wave has moved the layers of organisms in a sinusoidal manner.

In general the wave patterns were found between latitudes 9° and 13° S in June, July and August, in the area of the continental shelf. In this area the cold intermediate stream and the Benguela Current play an important part.

A fuller analysis of these, and similar, echo traces will be published later.

Gulbenkian Foundation Research Fellow,
Fisheries Laboratory,
Lowestoft.

VASCO VALDEZ

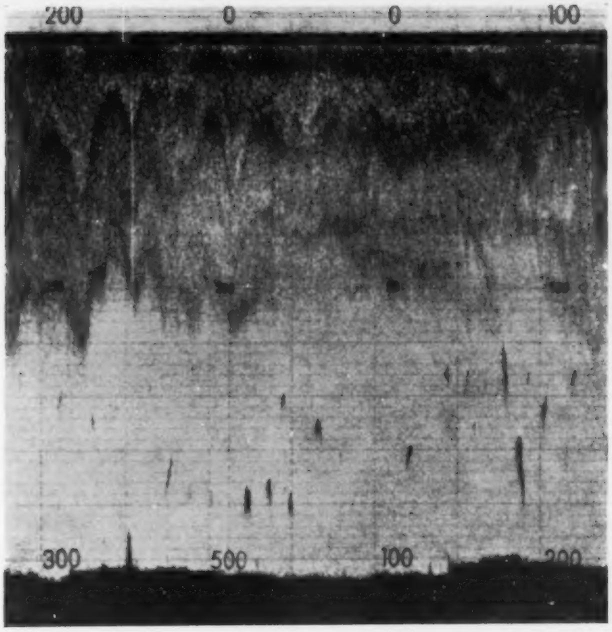

FIG. 1. Marked wave pattern in the scattering layer in the upper half of the echogram (Station 93 M.B.M., *Angola* ; 18.8.57 ; Lat. 10° 45′ 04″ S, Long. 13° 32′ 02″ E ; 11 miles off shore ; depth 100 m ; trawling 155° speed 3·2 knots from 11.30 hrs to 12.30 hrs – G.M.T. + 1 ; overcast).

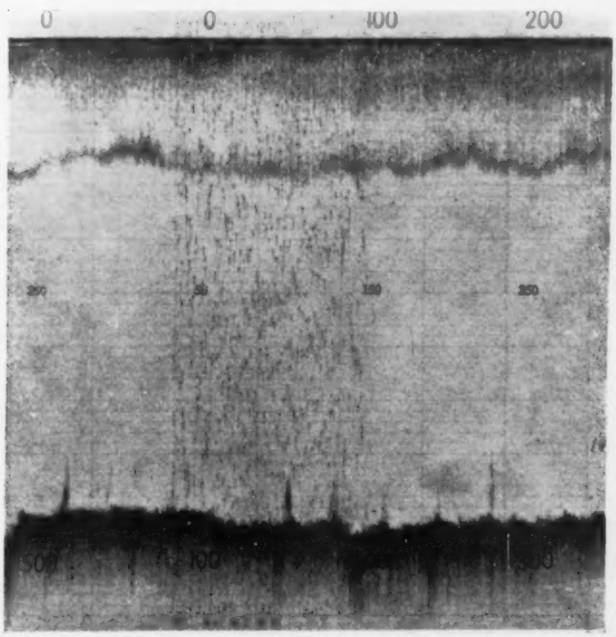

FIG. 2. A trace of noise, extending across all the paper record, which was associated with the presence of four killer whales following the ship. (Station 17 ; M.B.M., *Angola* ; 28.2.57 ; Lat. 16° 27′ 00″ S, Long. 11° 30′ 00″ E ; 13 miles off shore ; depth 93 m ; trawling 355°, speed 3·3 knots from 13.27 hrs to 14.25 hrs G.M.T. + 1 ; overcast).

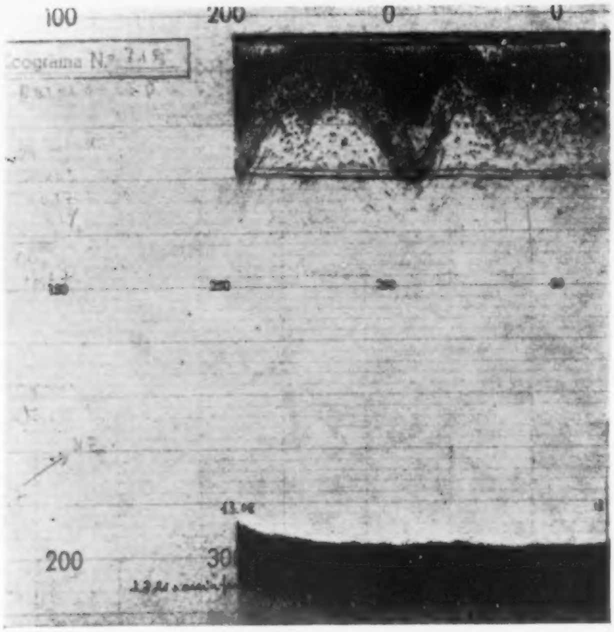

FIG. 3. Sinusoidal trace comprised of echoes from single fish and very small shoals. The upper surface of the sinusoidal trace is bounded by a compact mass. The parallel lines at 30 m are echoes from the anchor cable recorded by the side lobes of the receiver. (Station 50 M.B.M., *Angola* ; 27.6.57 ; Lat. 12° 10′ 05″ S, Long. 13° 30′ 00″ E ; 95 miles off shore ; depth 98 m ; anchored ; 1308 hrs to 1340 hrs – G.M.T. + 1 ; overcast).

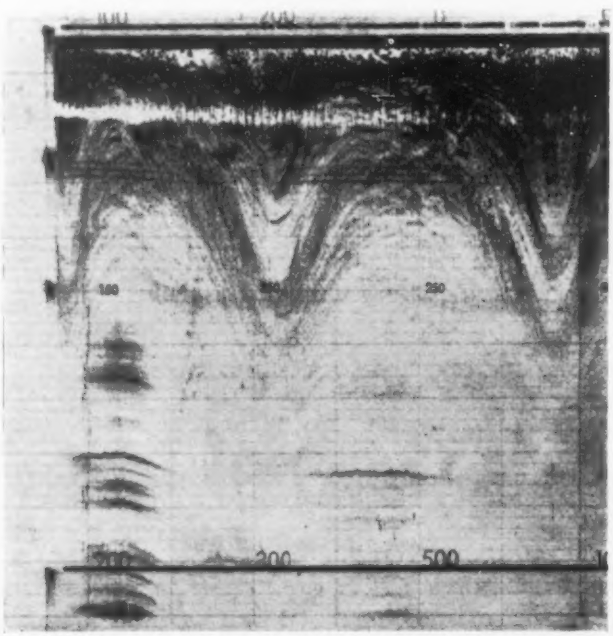

FIG. 4. Sinusoidal trace comprised of a complex of thin and diffuse layers. The three parallel lines at 30 m are echoes from the anchor cable recorded by the side lobes of the receiver ; the traces in deeper water on the left of the echogram are signals from the anchor cable received on the main beam. (Station 65 M.B.M., *Angola* ; 1.8.57 ; Lat. 08° 43′ 04″ S, Long. 13° 04′ 05″ E ; 95 miles off shore ; depth 110 m ; anchored ; 9.40 hrs to 10.25 hrs – G.M.T. + 1 ; overcast).

The Atmosphere and the Sea in Motion. Scientific contributions to the Rossby Memorial Volume, (edited by Bert Bolin, Stockholm University), Rockefeller Inst. Press, New York, in association with Oxford University Press, 1959. 509 Sieten mit vielen Abbildungen.

Dieses grossangelegte Werk ist als Gedächtnisband für Prof. Carl Gustaf Rossby gedacht, der am 19. August 1957 plötzlich in sienem Institut verschied und durch seine Persönlichkeit, durch seinen Charm und durch seinen überragenden Geist wohl als der hervorstechendste Wissenschaftler der Gegenwart auf dem Wissensbegiet der Geophysik, speziell der Meteorologie und Ozeanographie galt. Seine näheren Kollegen und Schüler haben sich zusammengetan, um ihn, dessen 60. Geburtstag in Kürze hätte gefeiert werden sollen, wenigstens nach seinem Tode der grossen Wertschätzung und tiefen Verehrung durch ein Memorial Volume zu versichern und es kann mit Recht gesagt werden, dass dies im vorliegendem Werk, dessen Redaktion in den bewährten Händen seines Stockholmer Schülers Bert Bolin lag, in ausgezeichneter Weise geschehen ist. Es trägt den Titel ' Atmospäre und Meer in Bewegung ' und kennzeichnet dadurch in bester Weise das Hauptarbeitsgebiet Rossby's selbst. Eröffnet wird es durch einen für einen weiteren Leserkreis bestimmten Aufsatz von Rossby selbst (Current Problems in Meteorology), der kurz vor seinem Tode verfasst, mit typisch Rossby–Schwung die Hauptprobleme der Meteorologie und Ozeanographie charaktersiert und durch treffende Beispiele erläutert. Tor Bergeron (Uppsala) und H. R. Byers (Chicago) geben den Lebenslauf und die wissenschaftliche Entwicklung von Rossby in zwei Aufsätzen mit jenem Einblick, den nur jene geben können, die ihn lange Zeit besonders nahe gestanden sind.

Den folgenden Hauptteil des Werkes füllen dann 46 wissenschaftliche Arbeiten seiner Kollegen und Schüler. Dieser Teil stellt eigentlich eine treffliche Darstellung des derzeitigen Standes unseren Wissens in den Hauptteilen der atmosphärischen und ozeanischen Dynamik dar und ist so von grosser Bedeutung als Ausgangspunkt für weitere Forschung auf diesen Gebieten der Geophysik. Es ist natürlich völlig ausgeschlossen, hier in dieser kurzen Besprechung alle diese bedeutsamen Arbeiten etwas eingehender zu besprechen. Aber ich will versuchen, wenigstens das wichtigste und für die weitere Entwicklung interessanteste möglichst kurz anzudeuten. Die Arbeiten wurden in 5 Gruppen zusammengefasst, die Hauptprobleme der Atmosphäre und der Ozeanographie entsprechen : Das Meer in Bewegung, Die stoffliche Verteilung im Meer und Atmospäre, Die allgemeine Zirkulation der Atmosphäre, Charakteristische Formen atmosphärischer Bewegungen und schliesslich Die Wettervorhersage.

In der 1. Gruppe findet man eine Arbeit von J. Bjerknes, Über neuzeitliche Erwärmung des Nordatlantik, eine Arbeit von Haurwitz und Stommel, Über die thermische Unruhe im Ozean, Dynamische Probleme behandeln P. Welander und W. Hansen, sowie H. Wexler, während G. O. S. Arrhenius die interessanten Fragen nach Anzeichen von klimatischen Änderungen am Meeresboden anschneidet.

In der 2. Gruppe behandeln Bolin und Eriksson das aktuelle Problem der durch die Verbrennung von fossilen Material bedingten Änderungen des Kohlendioxyd – Gehaltes der Atmosphäre, während im Anschlusse daran der letztere die Zirkulation noch von anderen atmosphärischen Bestandteilen des Meeres bespricht, und weiters Neiburger sich mit den meteorologischen Aspekten der Luftverunreinigung durch Oxydazionsprozesse in der Atmosphäre befasst.

Die 3. Gruppe ist wohl die wichtigste und umfasst 9 wissenschaftliche Arbeiten, die alle Fragen der atmosphärischen Zirkulation betreffen und bei denen die prominentesten Vertreter dieses Forschungszweiges (wie Kaplan, Charney, Fjørtoft, Palmén, u.a.) zu finden sind. Charney befasst sich hauptsächlich in theoretischer Hinsicht mit der allgemeinen atmosphärischen Zirkulation eines bestimmten Modells, das der wirklichen Atmospäre möglichst nahe kommt. Er sucht diese Zirkulation bis in ihre letzten Details abzuleiten und dann mit den Ergebnissen der Beobachtungen zu vergleichen. Fjørtoft gibt eine aufschlussreiche Diskussion über den Totalbetrag der kinetischen Energien in der Atmosphäre und ihrer Verteilung in derselben in Hinblick auf die Lage der äusseren

Wärmequellen und der Bodenreibung, während Palmén die bedeutsame Frage der Erhaltung der kinetischen Energie in der Atmosphäre in gewohnt klarer Weise behandelt. Mit ähnlichen Fragen beschäftigen sich auch Untersuchungen von Queney und vor allem van Mieghem u. Mitarb., die den Einflüssen einiger wichtiger Grössen (wie z.B. der kinetischen Energie, des meridionalen und zonalen Wärmeflusses und des westlichen Bewegungsmomentes ua.) auf die Ausbildung von Bewegungssystemen der verschiedenen Grössenskalen in der atmosphärischen Zirkulation ihr Augenmerk zuwenden.

Die 4. Gruppe enthält 12 interessante Arbeiten aus den Gebieten der synoptischen und theoretischen Meteorologie, die beide derzeit in ihrer Synthese zum erfolgreichsten Forschungszweig der Meteorologie geworden sind. Mit theoretischer synoptischer Meteorologie befassen sich die Arbeiten von Eliassen, Über die Frontenbildung in der Atmosphäre, von Fr. Defant, Über die hydrodynamische Instabilität in Zyklonenbereich und ihre Beziehungen zur Zyklogenesis und von P. D. Thompson, Über dynamische Wachstum und Okklusionsprozesse bei einfachen baroklinen Modellen. Zur theoretischen Meteorologie gehören auch die Arbeiten von Platzman, Eine Lösung der nichtlinearen Vorticity-Gleichung, von J. Holmboe, Über das Verhalten von baroklinen Wellen. Mit experimentellen Untersuchungen befassen sich die Arbeiten von Fultz u. Kaylor, sowie von R. R. Long. Mehr subtropischtropisch Meteorologische Fragen behandeln die Arbeiten Riehl s, Byers' und Markus und Witt.

In der 5. Gruppe ist vor allem die interessante zusammenfassende Darstellung von T. Bergeron über wissenschartliche Wetteranalyse und Wettervorhersage hervorzuheben, während die weiteren Arbeiten von Cressman, von Hinkelmann, von N. A. Phillips u.a. sich mit der Weiterentwicklung der numerischen Wettervorhersage befassen.

Überblickt man das ganze Werk, so kann man mit vollem Recht sagen, dass damit keinewürdigere und bleibendere Erinnerung an die wissenschaftliche Persönlichkeit Rossby's hätte geschaffen werden können. Man erkennt mit Genugtuung, dass seine Ideen und seine Arbeitsweise auf einen sehr fruchtbaren Boden der Forschung gefallen sind und für ihre Fortentwicklung man keine Sorge zu haben braucht.

A. Defant

Erich Bruns: **Ozeanologie, Einfürung in die ozeanologie, Band 1.** VEB Deutscher verlag der Wissenschaften. Berlin, 1958. 420 pp. 145 figures and 8 maps in folder.

Bruns' Ozeanologie is to take four volumes of which this is the first. It is also probably the dullest since Bruns classifies Ozeanographie as a factual description of the ocean, to be distinguished from Ozeanologie which he regards as a branch of geophysical science. Such classification is discussed in the first three chapters and is followed by an outline of the physical problems of the ocean and a long but incomplete table of the expeditions of research ships.

The book proper is in three parts: (a) An account of the distribution of land and sea, bottom topography, etc. (b) A description of charts, navigational aids and procedures, including navigation instruments and echo sounders. (c) Brief but useful summaries of bottom topography, currents, distribution of temperature, salinity and density, and of waves and swell. Available information is given not only for the oceans and their surrounding seas but also for some isolated seas. This is probably the most valuable part of the book – a geographical index supplements the subject index.

By its nature this first volume is utilitarian rather than exciting. It states the problems to be discussed in future volumes on oceanographic instruments, on scientific results and on possible forecasting techniques. The complete work should be a valuable contribution to the literature.

H. Charnock

Editorial Note
to the
Contributors to Deep-Sea Research

It has become more and more apparent that some papers submitted to *Deep-Sea Research* are (1) summaries of papers published or about to be published in other languages, or, (2) almost verbatim translations of such papers. On the other hand, on the inside of the back cover, there have long been certain statements of policy which it seems desirable to review at this time :

1. 'Papers submitted for publication will naturally be judged from the standpoint of scientific originality and novelty.' This means that *all* papers are sent to several persons competent to assess the content of the papers for this purpose. On the basis of such critiques, a decision is reached as to (1) whether to accept the paper, (2) whether to accept it after certain revisions and/or corrections, or (3) whether to reject it outright. In this way, a certain standard for *Deep-Sea Research* is maintained.

2. 'The preparation of progress reports and review articles is invited by the editors from time to time, and it is therefore requested that no uninvited contributions of this nature be submitted.'

3. 'Only papers that have not previously been published can be accepted for publication in *Deep-Sea Research*.' Thus, translations of papers or of summaries of papers originally written in another language and already published (or ' in press ') should not be submitted for publication in *Deep-Sea Research*.

The editors have hitherto been somewhat lenient in accepting such papers, but now that this journal is well-established, they must now try to adhere more rigidly to their stated policies.

A preliminary survey of thermal microstructure in the Strait of Gibraltar

ROBERTO FRASSETTO

(*Received* 23 *July* 1959)

Abstract—The 1958 survey provided the data for a preliminary synoptic study of the complicated dynamic phenomena of the Strait of Gibraltar. For this purpose, attention was focused near the boundary surface of the deep layer of pure Mediterranean water east of the sill. West of the sill this dense layer loses its character in a process of turbulent mixing with the lighter Atlantic water.

The survey of the thermal microstructure of the sill area was made possible by the use of the new towed thermistor chain of the Woods Hole Oceanographic Institution (RICHARDSON and HUBBARD 1959). In 66 crossings of the Strait (north to south) above the sill and one passage (west to east) along the axis, the following were the most interesting findings :

(1) – The boundary between deep Mediterranean water and Atlantic water oscillates vertically with tidal periods.

(2) – The boundary layer was found to slope down sharply at the centre of the channel at the time of internal high tide.

(3) – Vertical motions of the isotherms of semi-diurnal period and in phase with the moon transits were dominant.

(4) – Fluctuations of high amplitude and non-tidal period were superimposed on the dominant motions.

(5) – Solitary rapid depth variations of some isotherms were recorded more frequently over the southern portion of the sill. The maximum depth change recorded was 80 m.

(6) – The surface temperature is warmer on the Spanish than on the African side of the Strait. A four degree Centigrade difference was found at one time along the four-mile long traverse above the sill.

INTRODUCTION

History

A REVIEW of earlier work in the Strait of Gibraltar will be presented elsewhere. In this preliminary report, however, it is worth mentioning that the general yearly and seasonal changes in the hydrography of the Strait have been established (SCHOTT, 1928; Atlas der Dichte des Meerwasser; DE BUEN 1931, 1933). The data obtained from the *Thor* (NIELSEN, 1912) and the *Dana* (JACOBSEN and THOMSEN, 1934) is the most extensive and among the most accurate. NIELSEN (1912) and RAMALHO and DENTINHO (1931) agree that the strongest outflow of Mediterranean water occurs during the summer. Our measurements were made at this season, when the dynamics of the Mediterranean water are most clearly marked and are therefore easier to identify.

SCHMIDT (1922) and JACOBSEN and THOMSEN (1934) were the first to be concerned with the daily periodic changes in the hydrography of the main central channel of the Strait (limited by the 100 m bottom contour). Their presentation of the diurnal and semi-diurnal tidal fluctuations of the isothermohaline levels is the best to be obtained with repeated standard hydrographic casts. Short period oscillations (impossible to record with intermittent casts) superimposed on the tidal waves may have led JACOBSEN to some misleading conclusions.

Since internal waves may be one of the main characteristics of the hydrography of the Strait of Gibraltar, it is apropos to cite some of the more significant work in the field. In the Kattegat, at the entrance of the Baltic Sea, a situation analogous to the Strait of Gibraltar, H. Pettersson studied the periodic vertical fluctuations of the 30–31‰ isohalines discovering (among other things) a semi-monthly wave, Later Professor O. Pettersson (1935) defined this as 'an interval wave of lunar parallactic period' (about 13·6 days). Helland-Hansen and Nansen (1909) in various spots in the NE Atlantic found evidence of vertical oscillations of diurnal and semi-diurnal character at intermediate levels and having ranges up to 200 m. These were most pronounced in the vicinity of coasts or of shoaling bottoms. Defant, from the *Meteor* data, confirmed the existence of internal tides in mid-ocean and showed the existence of free internal waves of short period (about 2 hours) superimposed on semi-diurnal waves (Sverdrup *et al.*, 1942).

Professor De Buen (1933, p. 28) pointed out 'Chaque nouvelle croisière dans le Détroit de Gibraltar augmente, au lieu de diminuer, les difficultés pour trouver la loi générale qui préside aux rapports qui s'établissent entre les eaux méditerranées et atlantiques, et nous confirme dans notre idée sur la grande complexité des phénomènes dynamiques de cette région et dans la nécessité de continuer les études avec intensité.'

Newly designed oceanographic instruments which use a continuously recording system permit us today to conduct more adequate synoptic surveys, therefore we may feel more optimistic than Professor de Buen.

Recent Observations

In the general programme of the International Geophysical Year in the summer of 1958, the U.S. independently and France and Spain in collaboration took measurements in the Strait of Gibraltar. Lacombe and Lizeray (1959) obtained valuable current and T-S data in the western area. Tide measurements in a few harbours were obtained by Professor N. Menendez Garcia. The author made a survey of the eastern sill preliminary to a more complete series of measurements in the summer of 1959. Thanks to Dr. J. B. Hersey of the Woods Hole Oceanographic Institution, it was possible to obtain interesting data with one of the most advanced and unique instruments of oceanography. This report will present some of the results of that survey.

METHOD

The Instrument

The thermistor chain for Continuous Temperature Recording (CTR) was developed at the Woods Hole Oceanographic Institution. The chain is made of 11½ in. links faired with a plastic element. Twenty-three thermistors fitted in selected fairings are spaced about every 7·3 m to a depth of 168 m. Fifty conductors of 0·060 in. outer diameter run through a rubber insert inside the links. The conductors connect the recording system on deck with the submerged thermistors. A mechanical assembly was designed and constructed by Commercial Engineering Co. of Houston, Texas, and the temperature sensing and recording equipment by W. S. Richardson and C. R. Hubbard. With the winch it is a self-contained unit on a frame 8½ by 15 ft. which was installed on the stern of the USCGS *Yamacraw* for the 1958 summer expedition to the Mediterranean.

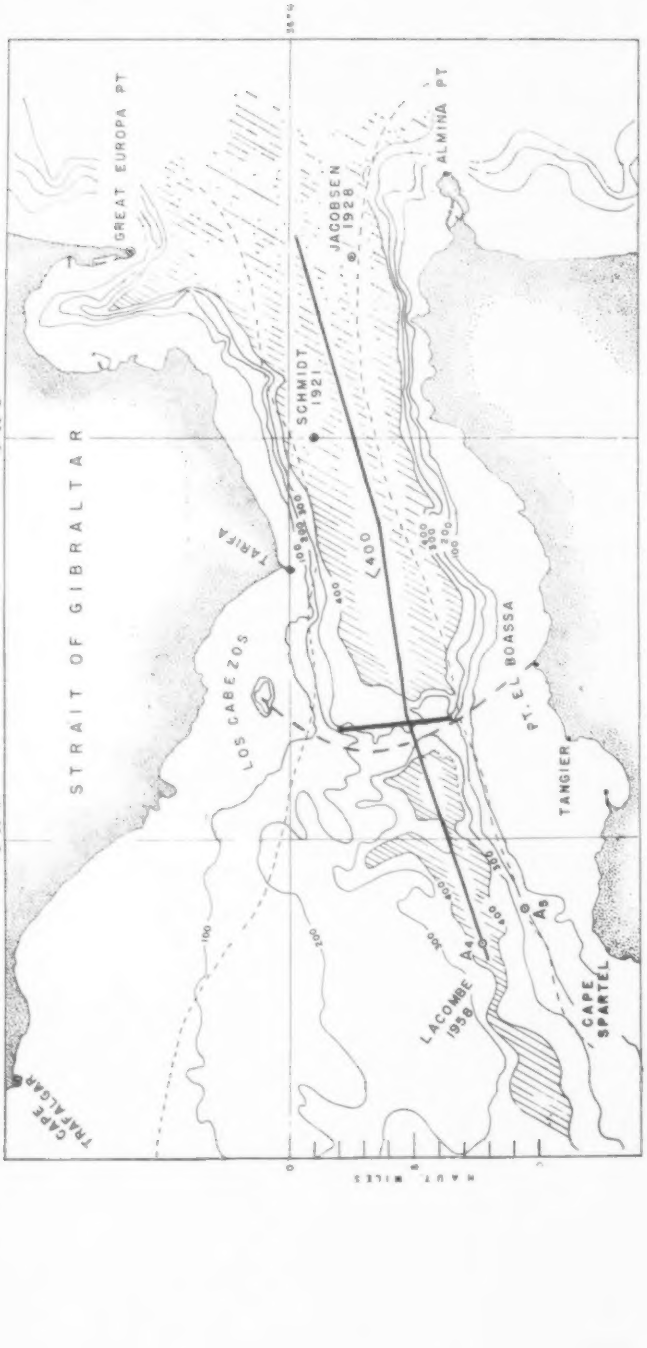

FIG. 1. Area of the Strait of Gibraltar with lines of survey (heavy lines). The bottom topography outside the sill was obtained from the Spanish Oceanographic Institute. It is based on the preliminary results of the *Xauen*'s 1956 survey. The eastern sill of the Strait lies along the arc (dashed line) from Los Cabezos (Spain) to Pt. El Boassa (Morocco). The stations taken by JACOBSEN and SCHMIDT are on the right, those taken by LACOMBE (A_4–A_5) on the left.

The chain can be lowered as desired, depending on the depth of the bottom. Because of the drag on the chain, the angle to the vertical changes with speed; thus the deepest thermistor rises as the speed of the ship increases (Table 1).

Table 1

Speed (knots)	*Depth (metres)*
0 to 1	168
3	160
6·5	154
10	140

The thermistors are carefully selected and calibrated. Their time constant is about $\frac{1}{2}$ second. The resistance, which varies with the temperature of each thermistor, forms one arm of a bridge which is connected and balanced to obtain a linear system. Starting with the uppermost thermistor, the thermistors are scanned in 7 sec and the instrument presents contours of equal temperature on a depth versus time record. The temperature range is from -2 °C to $+32$ °C. For detailed information of a more recent version of the recording system, see RICHARDSON and HUBBARD (1959).

Field Chronology

At the end of a Mediterranean cruise, the USCGS *Yamacraw*, under the leadership of Dr. EARL HAYS, left Cadiz on August 8, 1958 for the Strait to complete the thermal microstructure survey by midnight of August 10.

At a position 3 miles off Pt. El Boassa a buoy with a radar screen mast was anchored as a marker for accurate navigation. Because the buoy capsized during the first few hours of operation, navigational fixes were obtained by radar distances off Pt. Tarifa (north) and Pt. El Boassa (south), and were plotted every two minutes on tracing sheets over a Spanish chart for the Strait of Gibraltar (No. 402, scale, 1 : 52,000, edition 1956). This method was quite satisfactory as the fixed reference points never exceeded a distance of nine miles. Whenever the *Yamacraw* crossed the path of a ship she reduced speed to 3·3 knots or stopped, but manoeuvered to prevent drifting away from the selected axis before resuming the prescribed speed of 6·5 knots.

The west to east run with the thermistor chain along the longitudinal axis of the Strait was made at a speed of 11 knots upon entering the Mediterranean on July 7, 1958 (Fig. 1).

Bottom Topography

A detailed topographic survey of the sill north of Cape Malabata was made during the first part of the operation on August 8 using a Precision Graphic Recorder (P.G.R.) (S. T. KNOTT and J. B. HERSEY, 1956). It was set for a 4800 ft/sec send velocity. A star-like course with its centre on the vertical of the sill rise was followed. Because time was limited, this survey was made at 10 knots, a velocity too great to obtain the desirable 1/10-mile navigational accuracy. Therefore corrections had to be made by matching the sound lines before contouring the bottom.

In the final chart of the bottom topography (Fig. 2), the soundings from the P.G.R. records of the 66 runs across the Strait were used for greater accuracy. The soundings were not corrected for local sound velocity nor for slopes of the bottom.

The shoaling at the centre of the sill, which is inaccurately shown on most charts, was found to reach a shallow depth of 150 m (85 fms.). Because this was shallower than the full length of the thermistor chain (170 m), the thermal survey had to be made 8/10 of a mile east of the ridge to prevent the chain from hitting bottom.

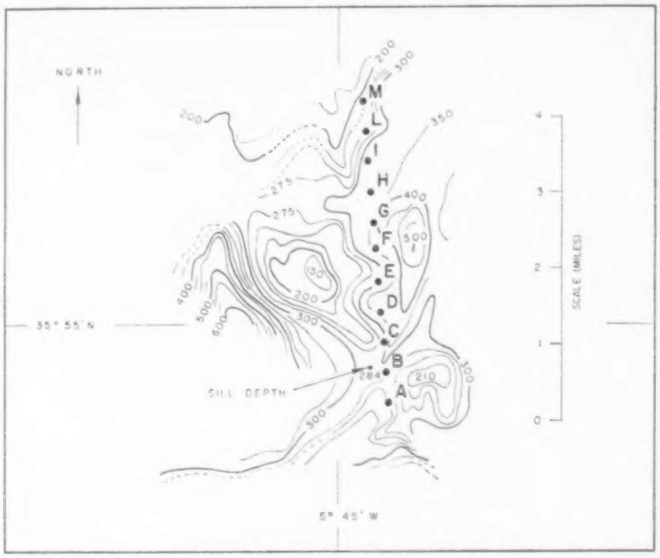

FIG. 2. Detailed bottom topography of the sill area area made by the *Yamacraw* during the present work. The dots with letters correspond to the fictitious stations described in the text. All depths are shown in metres.

P.G.R. records of the 66 crossings of the Strait indicate a very interesting and abundant presence of sound scatterers (Fig. 3). Various strata of sound scatterers appeared and disappeared at periodic intervals during the 52 hours of continuous recording. Further investigations of the scatters in this area should be made.

Thermal Microstructure Survey Across the Strait

The 66 runs back and forth above the sill (Fig. 1 and Fig. 4, bottom) covered an area four miles long, ½ mile wide at the southern end and ¾ mile wide at the northern end. The navigation of each run from south to north and return was plotted on a separate tracing sheet with fixes every two to three minutes. This was necessary in order to adjust the course to compensate for the lateral drift caused by surface currents changing continuously with time and location.

Thanks to the very efficient collaboration of scientists, officers, and crew of the *Yamacraw*, the desirable accurate navigation was maintained with success across the traffic line of the Strait. Only on one occasion, during the foggy night of August 8, did the ship have to stop for a relatively long period at the northern end of a run (as 16 ships were visible on the radar screen).

In processing the data at the laboratory the working area was given an axis oriented 355–175 degrees true, which was divided for convenience in stations 4/10 of a mile apart, from A (lat. 35° 54′N, long. 5° 44′W) to M (lat. 35° 58′N, long.

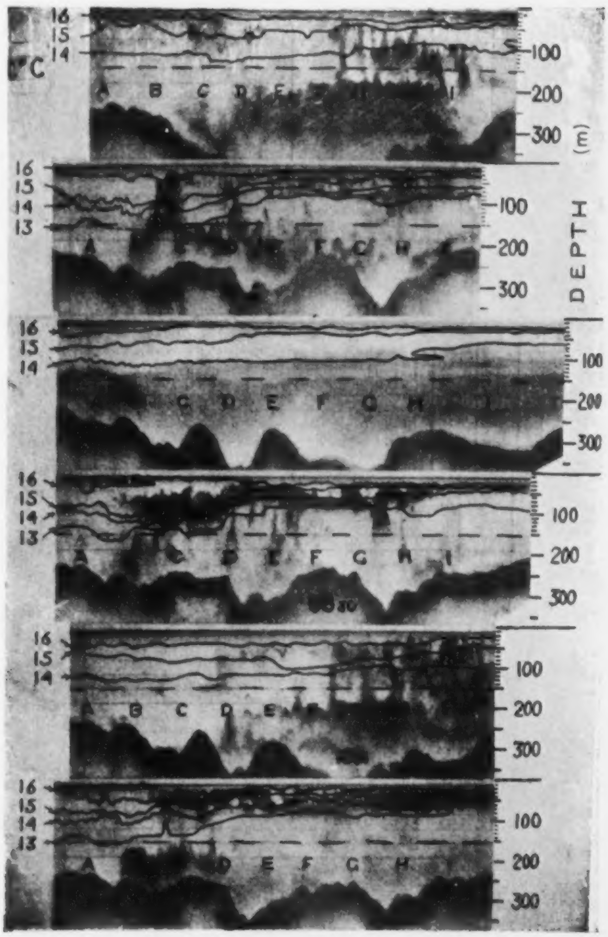

FIG. 3. Precision Graphic Recorder (P.G.R.) strips (selected from a group of 66) at approximately 6-hour intervals. Strips 1, 3, 5 indicate a possible low internal tide; strips 2, 4, 6, a high internal tide. The dashed line marks the depth of the deepest thermistor. Inked lines are the isotherms traced from the Contouring Temperature Recorder (C.T.R.). The letters indicate the position of the stations. Duration of each run is about 1/2 hour – the distance about 3·5 miles.

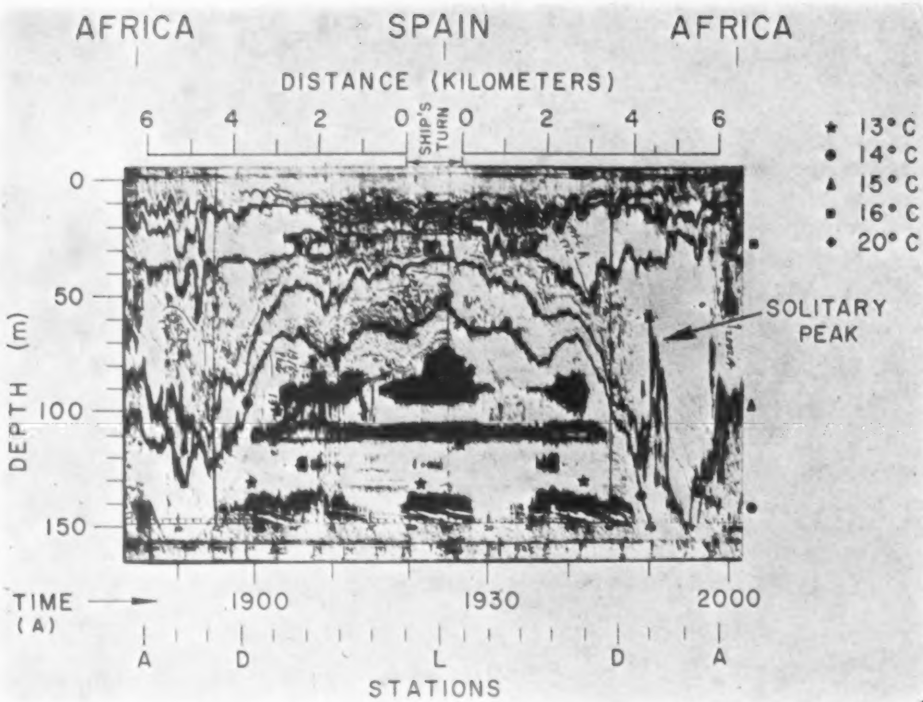

FIG. 4. Contouring Temperature Recorder (C.T.R.) sample showing the thermal microstructure across the Strait on a run from south (Station A) to north (Station L) and return, made between 1850 and 2000 hrs of August 9, 1958. The solitary temperature peak on the right is the highest recorded among the irregular depth changes of isotherms.

5° 44·5′W) (Fig. 2). In its navigation back and forth, the ship passed close to Stations E, F and G approximately every half hour and to Station A, or to Station L or M about every hour. Therefore, for all practical purposes, the data were obtained sufficiently near the axis to associate the vertical temperature changes of long period (semi-diurnal and longer) with those occurring at the stations (Fig. 2).

RESULTS AND DISCUSSION

The Mediterranean is a typical basin with an outflow of denser water across the sill which separates it from the Atlantic. To compensate for this loss and the great evaporation the lighter Atlantic water has a net surface inflow which, added to the

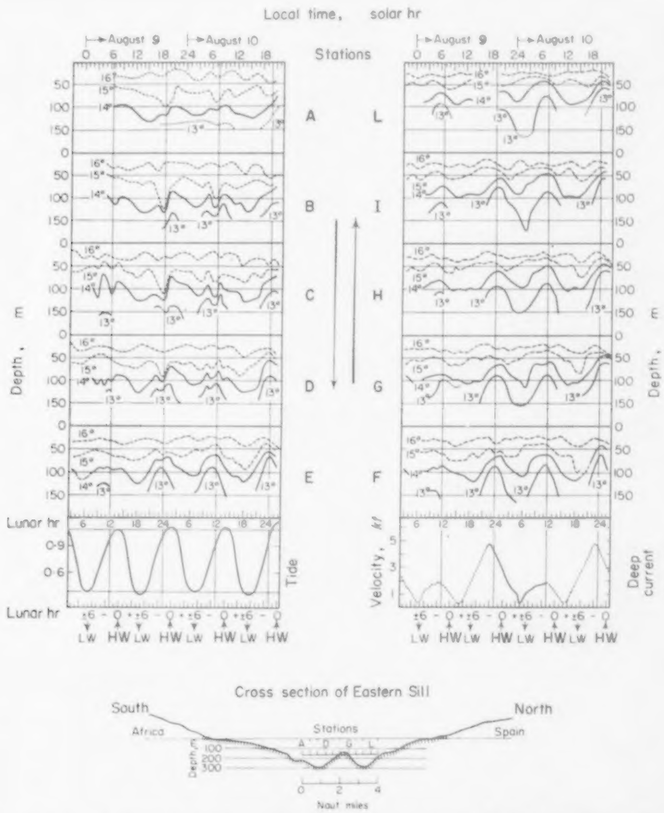

FIG. 5. Vertical oscillations of isotherms at ten stations (A to L) showing semi-diurnal period particularly regular for the 13 °C isotherm. Station B is placed next to Station L for contrast between the south and north. The bottom right curve represents deep current as measured by Sir JOHN MURRAY in 1910 at the same lunar time. The bottom left curve represents the predicted tides in Tarifa (from tables). At the bottom centre of the figure is a cross section of the sill along the arc from Los Cabezos (Spain) to Point El Boassa (Morocco) shown in Fig. 1. Local lunar time : 12^h is the upper local transit of the moon; 24^h is the lower transit.

small contribution of precipitation and net inflow from the Black Sea, restores the equilibrium (SVERDRUP, 1942, pp. 147–643). A characteristic of such a basin is that at and below the sill depth, the water in the basin is approximately homogeneous.

Observations made in the months of May, June and July of different years (SCHOTT, 1928; RAMALHO and DENTINHO, 1931) show that east of the sill the typical west Mediterranean bottom water is found below the 13 °C isotherm and the 38‰ isohaline. By observing the behaviour of the 13° C isotherm in time, we have a fair representation of the movements of the boundary surface of the bottom homogeneous water.

By the action of the Coriolis force on the net westward motion, the outflowing water mass should converge to the north (Spanish side) (SVERDRUP, *et al.* 1942). An indication of this effect is shown in the profile of the 13 °C isotherm (strips 2, 4 and 6 of Fig. 3), which steps up rapidly north of Station D, near the longitudinal axis of the Strait. This is also shown on the CTR record of one sample run from Africa to Spain and return (Fig. 4) and indicates that in the vicinity of the sill the north-south slope of the boundary surface is not gradual. Similarily, the inflowing surface water is deflected towards the south (Africa) where the 13° layer reaches greater depths.

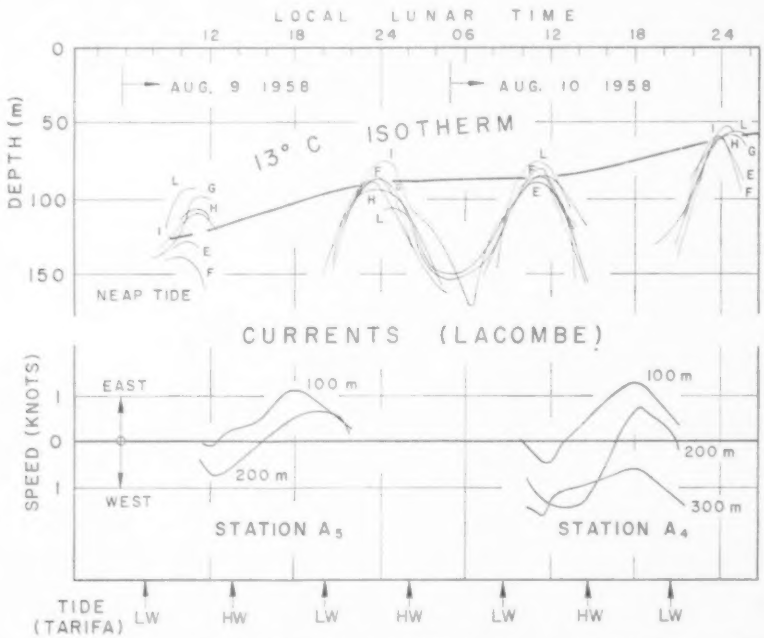

FIG. 6. *Upper section :* The semi-diurnal internal tides (13 °C curves of Fig. 4) from Station E to Station L (northern side of the sill) superimposed, reveal that the wave peaks rose from a depth of 125 m to a depth of 60 m (a total depth of 65 m) in four semi-diurnal periods (solid line = envelope). The measurements started at the occurrence of Neap tide.
Lower section : The east-west components of the currents, measured at Stations A_5 and A_4 by Professor LACOMBE are shown for phase comparison. The times of High water and Low water recorded in Tarifa by Spanish authorities are indicated at the bottom.

The strips in Fig. 3 were selected to show approximately the conditions across the Strait at about six hour intervals. In strips 1, 3 and 5, the 13 °C profile does not appear because at the time this isotherm lay below the deepest thermistor (dashed line) of the chain. Each pair of strips thus indicates a high and a low level of the

13 °C isotherm during 12 hour period. In order to reveal this periodicity in a wave form, the depth of the isotherms at each station, A to L, were plotted against time (local solar and lunar hours) after smoothing the temperature profiles on the records (Fig. 5). The southernmost (A) and the northernmost (L) stations are placed side-by-side for contrast. Table 2 shows the depth range in which the 14° and 15 °C isotherms were found at these stations. From this presentation of our measurements we notice

Table 2. Depth range of oscillations

Isotherm	*Station A (Africa)*	*Station L (Spain)*
14 °C	between 90 and 130 m	between 40 and 90 m
15 °C	between 55 and 95 m	between 30 and 60 m

that the smoothed lower isotherms in effect rise and fall with semi-diurnal periodicity. In the north this behaviour is roughly sinusoidal with time for the 13° and 14 °C isotherms. In the south, however, the lower isotherms have a more complex time dependence which seems to repeat approximately every 12 hours, but shows numerous changes of depth in time.

The 13° isotherm from the northerly stations are drawn superimposed in Fig. 6, where a consistent dependency on lunar time appears obvious. A steady rise in the peaks of the four tidal levels is pronounced on this plot.

East-west deep current velocities at the stations A_4 and A_5, about ten miles south-west of our location (from unpublished data of Professor LACOMBE) and the time of High and Low Water recorded at Tarifa are shown for phase comparison. During the night of August 9-10, while the range of the surface tide in Tarifa was of the order of 50 cm, we recorded a 13 °C isotherm range (from peak to trough) of about 75 m. It is apparent that this range varied in time from left to right of Fig. 6. The solid line indicates that the average peaks rose from a depth of 120 m to a depth of 60 m, a total of 60 m difference during the two days of our observations.

It may be significant that our measurements started on the night of August 8 at the occurrence of Neap Tide in Tarifa. It is possible that the amplitudes of internal tides change with the influence of the cycles of the lunisolar gravitational force, which is responsible for the known Spring and Neap surface tides.

Until now we have presented the observations in a vertical plane across the Strait during the times of single runs. In Fig. 7 we present the thermal microstructure in horizontal planes, at 25 m depth intervals to show more clearly how it changes with time. The 8 m isobath is used to represent the surface because above this depth, with the thermistor chain, one would measure temperatures in the ship's wake. In this figure we plotted the temperatures corresponding to each depth across the Strait from A to L (ordinates) as a function of local lunar time (abscissa). In this presentation the interplay of the water masses in time is evident. The 8 m isobath shows that during the night of August 8-9 the temperature on the north (L) was 4° higher than on the south (A). This situation changed rapidly as the days progressed but it seems that there is an indication of a 24-hour period in the north-south thermal structure (peaks at about 24 hours lunar time). It is not possible to state whether the wind had any influence on the temperature variation at this depth. We will mention that strong winds of gale force blew from the east in the Mediterranean on

August 8. These were followed by calm weather on August 9, 10 and 11. The thermal microstructure of the 25 m isobath appears rather complex while the 50 m one is more homogeneous in time. At 75, 100, and 125 m the periodicity of the isobaths with time and the changes from north to south are strikingly shown.

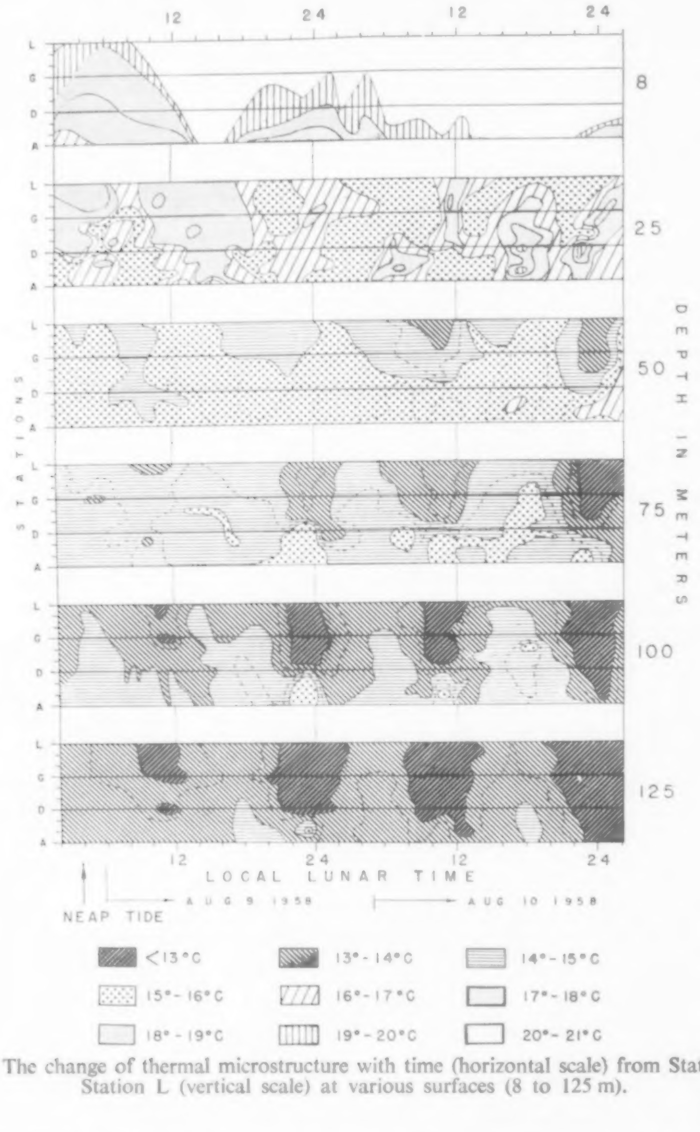

FIG. 7. The change of thermal microstructure with time (horizontal scale) from Station A to Station L (vertical scale) at various surfaces (8 to 125 m).

On the cross section A-L it was observed the large oscillations ranging from 1 to 20–30 m take place continuously in the isotherm's depth, particularly on the southern side (A–D). Larger solitary peaks of the 15°–16 °C isotherms appeared at times in the vicinity of Station C and seemed to recur at intervals of about six hours. The most

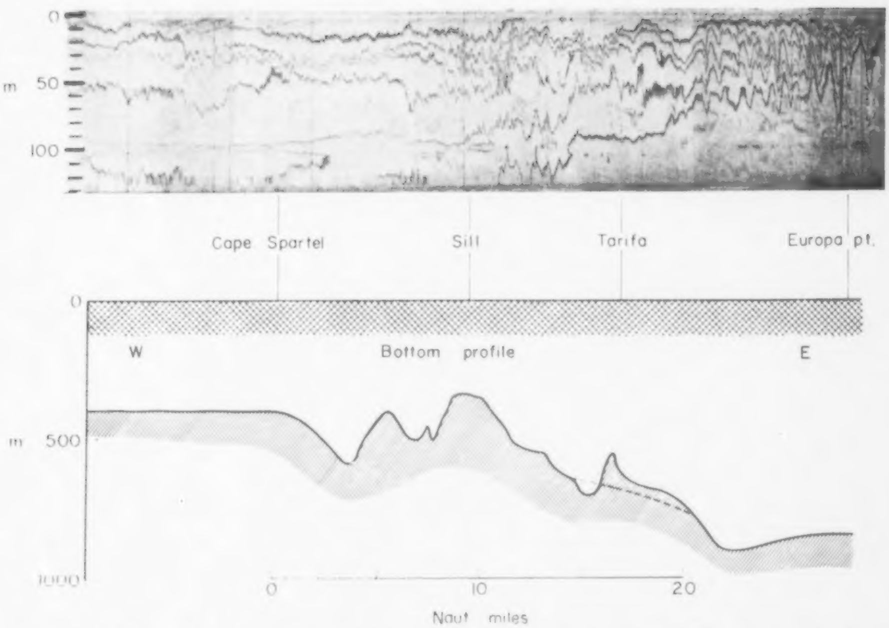

FIG. 8. Detail of the C.T.R. record from the sill to Point Europa (Gibraltar), showing short-period internal waves of varying character and shoaling of the isotherm towards the right (Mediterranean). The ship was moving on a course E-N-E at 11 knots.
(Below). Longitudinal cross section : C.T.R. record and bottom contour of the run from the Atlantic to the Mediterranean, as shown on survey line of Fig. 1. Stippled area represents the depth survey with the thermistor chain.

pronounced peak (85 m high) which was recorded on the 15 °C isotherm, is shown on the right of Fig. 4. It is possible that the local peaking was caused by a large eddy.

In general, the temperature curves do not suggest appreciable vertical mixing so that variations in isotherm depth may be the result of horizontal mixing, or of the motion of internal-type waves. The possibility of explaining some of the features by internal wave motion becomes more intriguing when the temperature profiles (Fig. 8), obtained between Cape Spartel and Europa Point, on the July west-east 30-mile long run are examined. Here the waves are shown as obtained from a boat travelling at 11 knots. A shoaling and the highly oscillatory nature of the isotherms towards the east (right side) is evident.

The measurements presented here illustrate the complexity of the motion of Gibraltar waters. Speculation on the causes of this motion has been minimized in this report but will be included in a future, more detailed, study which includes additional data obtained in later tests. The author has completed a ten days thermal structure survey in the Strait during July, 1959, and it is hoped that further information, particularly on the internal waves, may result from the analysis of the data.

RECOMMENDATIONS

From our preliminary survey it appears that measurements made with the older oceanographic standard instruments may not reveal important features of the complex dynamics of the Strait of Gibraltar. It appears that continuously recording instruments and synoptic methods with long period observations are particularly important here. Measurements both at Neap and Spring tide are necessary for each series at the same station.

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Some chemical and hydrographic observations along the north coast of South America—I. Cabo Tres Puntas to Curaçao, including the Cariaco Trench and the Gulf of Cariaco

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Abstract—Chemical and hydrographic observations were made on five north-south sections along the Caribbean coast of Venezuela in October and November, 1958. In addition, 15 stations were occupied in the Gulf of Cariaco. Chemical determinations included dissolved oxygen, total and inorganic phosphorus, nitrate, silicate and, in the anaeric waters of the Gulf of Cariaco and the Cariaco Trench, hydrogen sulphide.

Except for some low-salinity near-surface water, these waters form a single mass, on the basis of the temperature-salinity diagram, in agreement with the findings of Parr (1937). Minimum salinities are found at 700–800 m and can be attributed to Antarctic Intermediate sources. Maximum salinities are in the upper 200 m, at depths which increase to the north.

Near the coast, isopleths of salinity, temperature, density and the nutrient ions generally slope upward toward the south, particularly in the eastern sections. This is interpreted as evidence of upwelling along this coast, a phenomenon which appears to be the only important source of nutrients in the photic zone, and which accounts for the high biological productivity of the region.

The Gulf of Cariaco was filled with nearly isohaline water having the same temperature correlations as the Caribbean water outside at the time of the observations. Upwelling at the eastern end of the Gulf is clearly evident from the temperature, oxygen and nutrient distributions. The water deeper than about 54 m is isolated from, and is colder than, water at equal depths outside. Past observations indicate that this deep water may be renewed some (and possibly all) years, in February. These deep waters are isolated, vertically, by a sharp temperature gradient, are stagnant, and contain sulphides. The upwelling in the east results in high biological productivity in the region, which is evident from the rich flora and fauna.

An estimate of the productivity of the region has been made from the fixation of phosphate-phosphorus which upwells near the coast, north of Puerto La Cruz. The calculation indicates a production of 0·14 gm C/m^2/day, a figure which is consistent with estimates made in the region by other methods. An estimate made in the Gulf of Cariaco, also on the basis of the fixation of inorganic phosphate, indicated a daily production of 2·8 to 5·7 gm C/m^2.

Summario—En octubre y noviembre de 1958 se hicieron algunas observaciónes químicas e hidrográficas a lo largo de la costa Caribe de Venezuela. En el curso del trabajo la temperatura y la constitución química de las aguas de la región fueron estudiadas en forma de cinco secciones a lo largo de la costa en sentido norte-sur y además en 15 estaciónes hidrográficas en el Golfo de Cariaco. Los estudios químicos incluyeron análisis del oxígeno dissuelto, del fósforo inorgánico y totál, nitrato, silicato y, en aguas anaéricas del Golfo de Cariaco como en la Trinchera de Cariaco, sulfito de hidrógeno.

Con la sola excepción de un tanto de agua de baja salinidad cerca de la superficie, el agua formó una sola masa según el diagrama de temperatura-salinidád, de acuerdo con los resultados de Parr (1937). Las salinidades mínimas, encontradas entre 700 y 800 metros de profundidád, pueden atribuirse a las aguas de crigen Antártico Intermedio. Salinidades máximas se encontraron a profundidades de 200 metros o menos, según la distancia de la costa. La salinidád máxima se encuentra cerca de la superficie en las regiones costeras, y a mayores profundidades hacia el norte.

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Cerca de la costa, las superficies de igual salinidád, temperatura, densidád y sales nutritivas se inclinan hacia la superficie hacia el sur; esta tendencia se nota especialmente en las secciones orientales. Tal inclinación se interpreta como seña de surgencia de aqua de niveles inferiores a lo largo de la costa, lo cuál eleva el aqua de mas alto contenido de sales nutritivas hacia la superficie y la zona fótica. Esto explica la elevada producción biologica que se encuentra en la región.

El Golfo de Cariaco se halló lleno de agua casi isohalina la cual tuvo las mismas characterísticas de temperatura como las aguas del Mar Caribe en la vecinidád. El fenómeno de surgencia de agua de niveles inferiores ocurre en la región oriental del Golfo según la distribución de oxígeno dissuelto, temperatura, y sales nutritivas. El agua a profundidades majores de approximadamente 54 metros está aislada y posée temperaturas menores a las que se observan a profundidades iguales en el mar afuera del Golfo. Observaciones obtenidas en tiempos pasados indican que estas aguas mas profundas del Golfo suelen renovarse en algunos años, y posiblemente cada año, en febrero. Estas aguas de produndidád se encuentran aisladas por medio de un distinto cambio en la distribución verticál de temperatura; por lo tanto, se hallan estancados y contienen sulfido de hidrógeno. La producción biologica de la región del Golfo es elevada gracias a la surgencia de agua de niveles inferiores en la porción oriental; la abundancia faunística y florística son testigos a esto.

Fué possible calculár la producción biologica al norte de Puerto La Cruz por medio de las observaciones de contenido de fosfato cerca de la costa. Los resultados indican que 0·14 gramos de carbón se fijan por metro quadrado por dia. Este presupuesto está de acuerdo con los resultados de otras investigaciones en la región, las cuales se hicieron con otros métodos. En el Golfo de Cariaco, un presupuesto de la producción biológica por medio del fosfato dió como resultado desde 2·8 a 5·7 gramos de carbón fijados por metro cuadrado y por día.

INTRODUCTION

THE RELATIONSHIPS of the hydrography and the chemistry of the inshore regions of the southeastern Caribbean Sea to biological productivity and to deposition of sediments in the area are the principal foci of interest in the present study. Other

Table 1. Hydrographic stations occupied in the Southeastern Caribbean region.

	Station numbers	*Inclusive dates*	*Publication*
Atlantis	1502–1507	14–22/III/33	Bulletin Hydrographique pour l'année 1933 (1934).
Atlantis	2751–2799	13–25/I/37	Unpublished.
Atlantis	5231–5235	5/XII/54	To be published in Bulletin Hydrographique pour l'année 1954.
Atlantis	5266–5271	8–10/II/55	To be published in Bulletin Hydrographique pour l'année 1955.
Atlantis	5596–5607	1–9/IX/57	To be published in Bulletin Hydrographique pour l'année 1957.
Atlantis	5659–5697	28/X–6/XI/58	To be published in Bulletin Hydrographique pour l'année 1958.
Crawford	332–350	22–25/II/58	Metcalf (1959)

N.B.—*Reduced station data may be had upon application to the Director, Woods Hole Oceanographic Institution.*

discussions of the hydrography and chemistry of the Caribbean (PARR, 1937a, 1937b, 1938; SEIWELL, 1938; RAKESTRAW and SMITH, 1937; WORTHINGTON 1955, 1956) have dealt with more general offshore phenomena, and have left questions concerning inshore events to inference. However, this region should be of more than ordinary

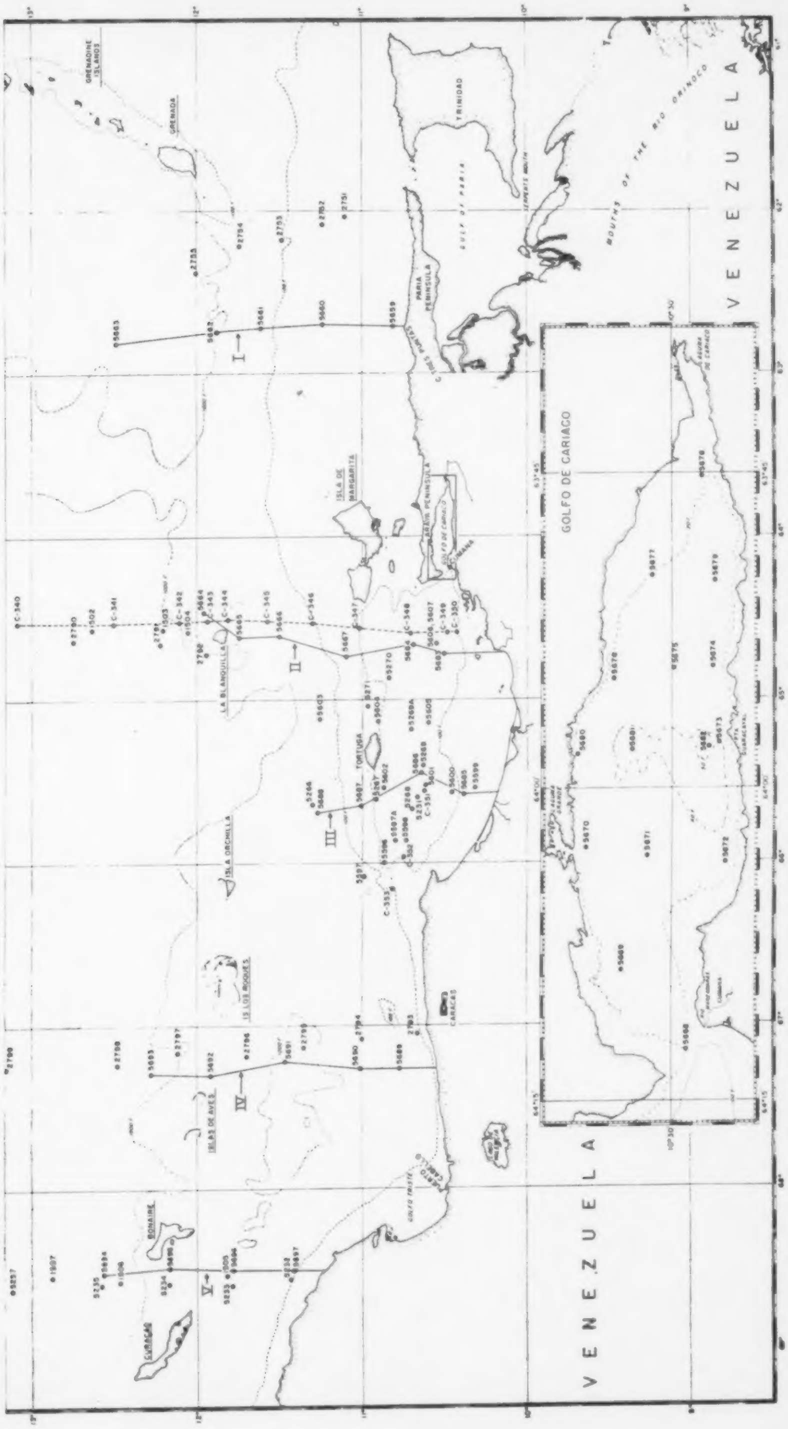

FIG. 1. Stations and hydrographic sections occupied in the region by R. V. *Atlantis* and R. V. *Crawford*. *Crawford* station numbers have the prefix 'C.' Dates of the stations are given in Table 1.

oceanographic interest, characterized as it is by upwelling along the coast; by the anaeric Cariaco Trench (RICHARDS and VACCARO, 1956; RICHARDS and BENSON, 1960); and by the Gulf of Cariaco, which, although it has a fjord-like topography and a remarkably high rate of organic productivity, has no significant fresh-water influx.

The hydrographic and chemical observations in the Gulf of Cariaco are, to the best of our knowledge, the first made there. The Gulf, an embayment between the Araya Peninsula and the main coast of Venezuela, is a little over 35 miles long (east to west) and 9 miles wide (north to south). Its opening to the Caribbean, about 2 miles wide (near the city of Cumana), has a sill depth of about 54 m. The fairly regular bottom is indented by a centrally located basin having a maximum depth of about 80 m a little north of Punta Guaracayal (Fig. 1).

The Araya Peninsula is arid, but the land to the south rises steeply, and enjoys sufficient orographic rainfall to support a tropical vegetation. Small streams with small watersheds enter the head of the Gulf through Laguna de Cariaco, but during the period of observation there was essentially no fresh water in the nearly isohaline Gulf, where salinities varied only between 36·60 and 36·70‰. Thus, the density stratification and stability in the Gulf were largely thermal effects.

The discussion is based, for the main part, on observations of salinity, temperature, dissolved oxygen, inorganic and total phosphorus, nitrates and silicates made on Cruise 246 of R.V. *Atlantis* in October and November, 1958. All sources of the data which are used are given in Table 1 and FIG. 1.

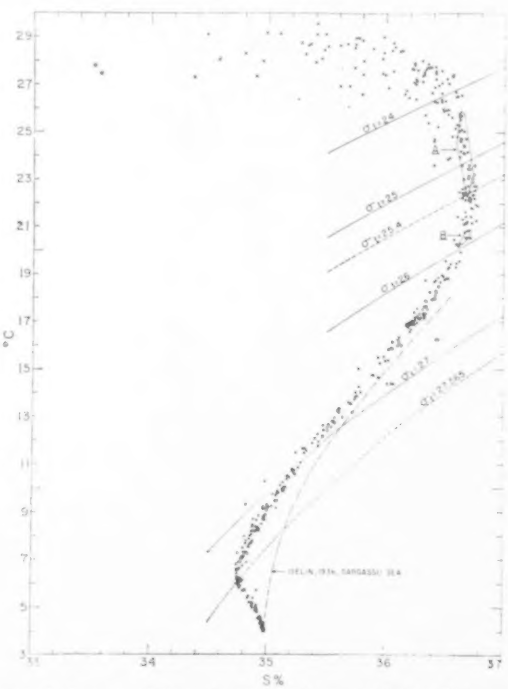

FIG. 2. Temperature-salinity correlations in the regions studied and in coastal waters to the west. The line indicated is the T/S correlation ISELIN (1936) found for the Sargasso Sea. Areas A and B enclose all the points from the Gulf of Cariaco.

WATER MASSES OF THE REGION

Insofar as water masses are characterized by the salinity-temperature diagram (Helland-Hansen, 1916), all of these north coastal waters, with exceptions in the superficial warm layers, are of a single type (Fig. 2) which has been discussed by Parr (1937a). Maximum salinities, greater than 36·5‰, are found in the upper 200 m, and are associated with σ_t values of 25·4. Parr attributes this maximum salinity water to a wedge, of Sargasso Sea origin, which penetrates to the southwestward and through the passages between the Greater Antilles and northern Lesser Antilles and which both overlies and underlies water of North Equatorial origin entering the more southerly of the passages between the Lesser Antilles. Salinity minima occur near $\sigma_t = 27{\cdot}365$, the value found by Parr, at about 6 °C and 700–800 m in depth. This low salinity water stems largely from the Antarctic Intermediate water mass, has large negative salinity anomalies (computed from Iselin's 1936 diagram) and high silicate concentrations (Richards, 1958). This σ_t surface (27·365, Parr's value) represents the core of the Antarctic Intermediate water in the region. The deeper, colder waters of the Caribbean are additionally different from extra-Caribbean waters by virtue of their lower oxygen and higher nutrient-salt concentrations.

LOW-SALINITY SURFACE WATER

In the Caribbean region included in Fig. 1, there is a general trend for surface salinities to decrease and for surface temperatures to increase northward from the coast. This trend is clearly shown in the *Meteor* atlas of surface salinities and temperatures (Böhnecke, 1936) and by Parr (1937a, 1938). This distribution is apparently the result of upwelling, which brings colder, more saline water to the surface along the Venezuelan coast. Imposed upon this general distribution of surface salinity are tongues or streaks of even fresher water of extra-Caribbean origin. As shown by Böhnecke, the latter has two sources : (a) South American rivers and (b) the equatorial North Atlantic. According to van Andel and Postma (1954), low-salinity water flows north-westward along the northeastern South American coast around both sides of the island of Trinidad, to enter the Caribbean between Grenada and the Paria Peninsula. The *Meteor* atlas indicates that the contribution of the Orinoco River to this source is relatively minor in comparison with the Amazon, but according to Postma (private communication) the Orinoco water may be of major importance in the Caribbean. Böhnecke's charts indicate that the influence of the South American rivers on the Caribbean is slight from January until May, and although by May these waters have spread upward along the Brazilian and Guiana coasts to the latitudes of the Windward Islands, surface salinities between the Paria Peninsula and Grenada are not less than 35·5‰. Surface salinities lower than 35·5‰ are found in the Caribbean beginning in June and increasing in their range until July, when values lower than 33·75‰ may be observed west of the Windwards. After July, this fresher water recedes from the Caribbean for the rest of the year. By October, water less saline than 35·0‰ from the equatorial North Atlantic joins with that from the South American rivers, forming a continuum from the Venezuelan Basin to the West coast of Africa, but by December the two sources are again separated by water more saline than 35·0‰, and Böhnecke shows no water fresher than 35·5‰ in the Caribbean region (Fig. 1) in December. Although the available hydrographic sections are

inadequate to describe the course of this low-salinity water in detail, they are in general agreement with BÖHNECKE's charts. In January, 1937, water less saline than 35·5‰ was observed at the surface at Stations 2751, 2752 and 2753, and was apparently attributable to South American river discharge. During this 1937 cruise, the low-salinity water was sufficiently dissipated to be no longer evident as a salinity minimum in a section along 67 °W, nor was the low-salinity surface water evident in the February 1958, *Crawford* section (FIG. 3), which, although in good detail along 64° 30′W, was

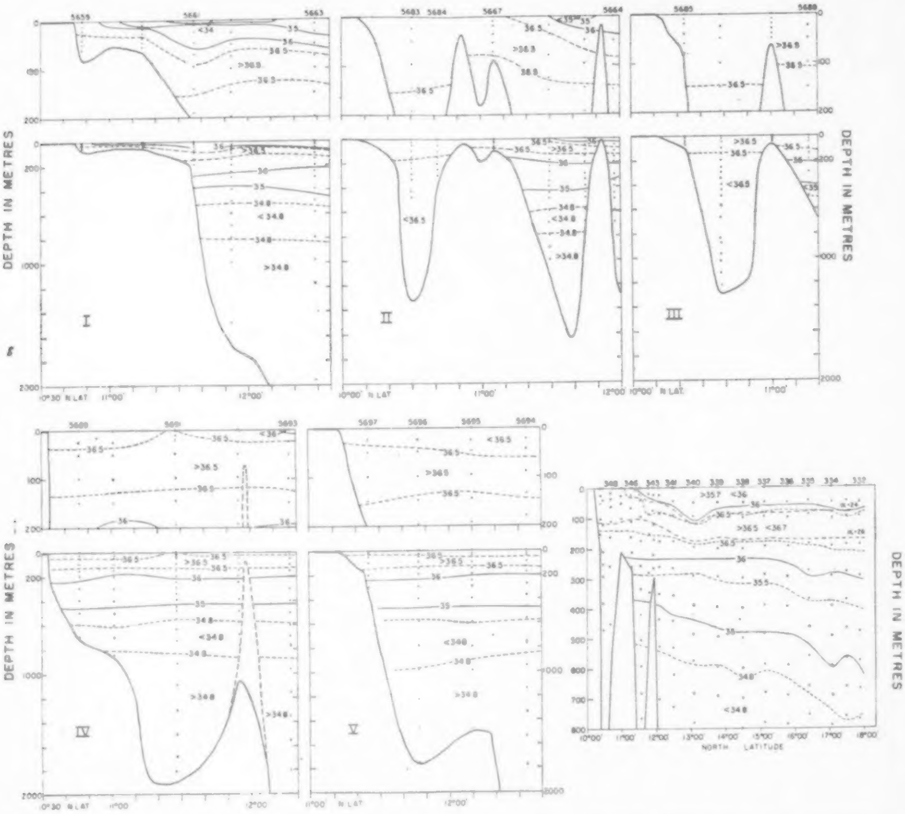

FIG. 3. Salinity sections. Numbers I through V occupied by *Atlantis*, October and November, 1958. The lower right section occupied by *Crawford*, February, 1958.

occupied during the dry season. On the other hand, low-salinity water was clearly present at the time of the October-November *Atlantis* observations, centered at Station 5661 (FIG. 3, Sect. I, minimum salinity 33·52‰) and at Station 5665 (Sect. II, minimum salinity 34·94‰). However, the surface salinities in Section IV of this cruise steadily decrease in the northward direction, and none are sufficiently low to distinguish low-salinity water of Atlantic origin from the general trend, a distribution similar to that observed at these latitudes in January 1937.

As has been indicated in the introduction, the water of the Gulf of Cariaco was, at the time of the observations, essentially isohaline. The points from the Gulf

fall on the temperature-salinity diagram for the general region without anomalies, but are divided into two groups (Areas A and B, FIG. 2), according to whether the samples were from above or below sill depth. Areas A and B of FIG. 2 are sufficiently separated to emphasize the isolation of the bottom, stagnant water below sill depth.

The Cariaco Trench is a unique locality of stagnation (RICHARDS and VACCARO, 1956). From 600 m to the bottom at about 1400 m, it is as nearly isohaline as the precision of the salinity determinations permits one to judge. Between its sill depth (*ca.* 150 m) and 600 m, salinities are higher than those at equal depths outside the

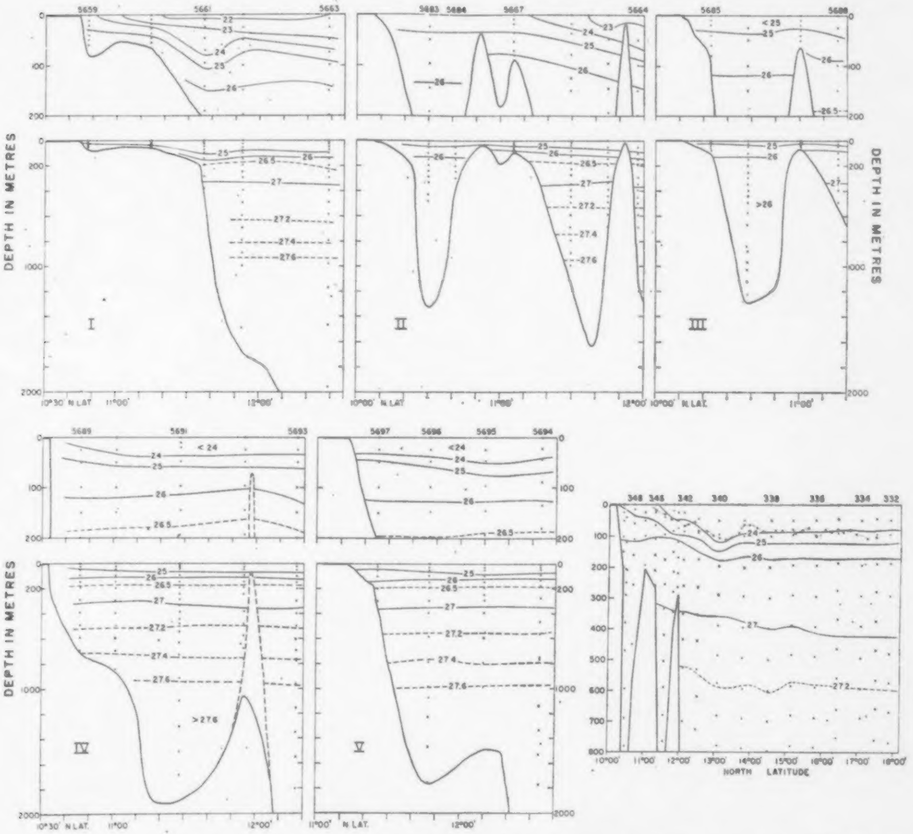

FIG. 4. Density (σ_t) sections. The sections are those shown in FIGS. 1 and 3. The line – – – + – – – – + – – – – shows the bathythermometrically determined depth of the upper isothermal mixed layer.

trench, immediately to the north (Stations 5683, 5684, 5685, 5686, FIG. 3). Somewhat below the sill depth, the density *in situ* in the trench (FIG. 4) is less than at the same depths in the open Caribbean, because of the higher temperatures inside. The distribution of density across the sill is critical to the trench's remaining unflushed, but the observations which have been made do not permit determining the extent, if any, of advective replacement of the anaeric waters in it. The chemical conditions in the trench indicate that at most the flushing is slow, weak, or intermittent.

To recapitulate, the temperature-salinity diagram (FIG. 2) shows the water of this region to be of a single type, with relatively small, surface-borne accretions of fresh water entering the system from the surface of the Atlantic. These accretions fluctuate with the rainy and dry seasons.

MERIDIONAL DISTRIBUTION OF SALINITY AND TEMPERATURE

In general, the surface waters in the southern part of this region are more saline and colder than they are to the north (FIG. 3). Sigma-t surfaces (FIG. 4) at depth are nearly level (in the north-south direction), but there is a slight upward tilt, to the south,

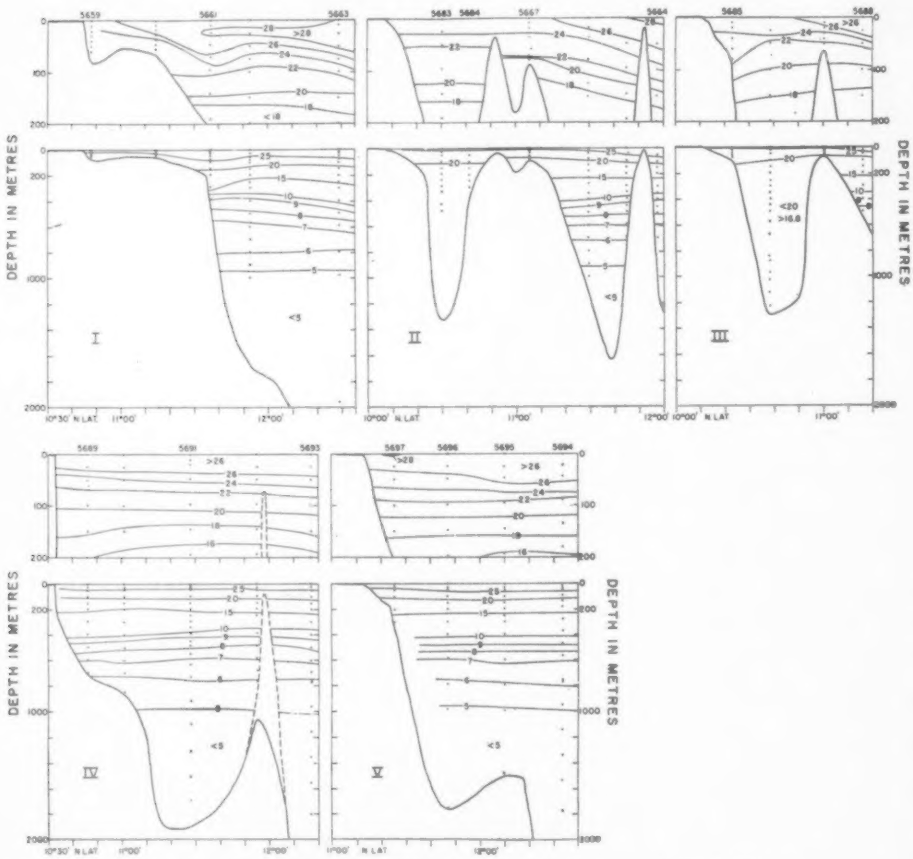

FIG. 5. Temperature sections (*Atlantis*). The locations are shown in FIG. 1.

of the isopycnals in the upper 200–300 m. These observations and the chemical observations indicate upwelling along this coast. This upwelling is apparently the only continuing source of the nutrient-salt supply responsible for the high basic productivity and biological populations of the region, because the nutrient levels in the surface waters entering the region are uniformly low.

DISTRIBUTION OF TEMPERATURE

The surface temperatures in the region (FIG. 5) varied from 21·22° to 28·59 °C, and in general the lowest were found nearest the coast. In the upper 100 m, the isotherms slope upward, to the south. This upward slope is more extreme in the

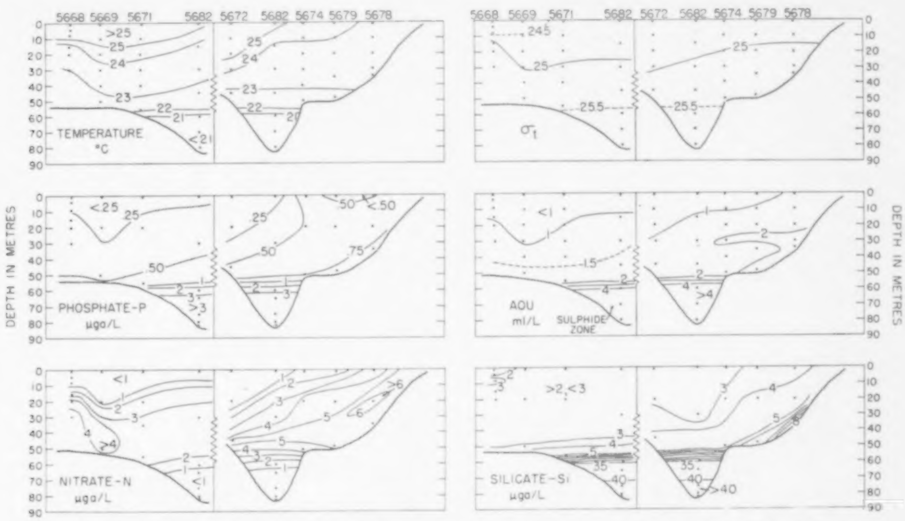

FIG. 6. Physical and chemical variables in a section along the length of the Gulf of Cariaco. Station locations are shown in FIG. 1.

eastern three sections, and in Section I the warmest water was found below the surface at Stations 5661, 5662 and 5663 (FIG. 5). At greater depths, the isotherms were nearly level. No water warmer than 5 °C was found at depths greater than 1000 m.

TEMPERATURES IN THE GULF OF CARIACO

The surface temperatures in the Gulf (FIG. 6) gradually decrease to the eastward, dropping from 25·8 °C at the mouth of the Gulf to 23·9 °C at the head. At the time of the observations, water at about 22·5 °C could enter the Gulf over the sill. This cold water appears to flow into the Gulf over the sill and then to rise to the surface layer in the eastern reaches of the Gulf.

The Gulf waters deeper than about 55 m are isolated from the open Caribbean by the shallow sill. In the deeper basin of the Gulf, there is a relatively steep thermal gradient between the sill depth (54 m) and 60 m, the temperature dropping at least 1·5 °C in this vertical distance. This gradient establishes a high order of vertical stability and a considerable barrier to vertical mixing of water from depths greater than 60 m. Water as cold as 20·37 °C was observed in the depths of this basin. This cold water was stagnant, oxygen-free, and contained hydrogen sulphide. During the period of observation, 20·4 °C water was not present at depths less than about 120 m at the nearest station occupied outside the Gulf. However, five hydrographic stations (Table 2) are available from the Cariaco Trench, to the west of the mouth of the Gulf of Cariaco, which show something of the temperature variability in this part of the water column. On only one of these occasions, 9 February 1955, was the outside

water at depths between 50 and 80 m sufficiently cold to supply the now anaeric water filling the deepest part of the Gulf. This situation was also approached on 25 February 1958, so there may be either annual or intermittent flushing of the basin.

Table 2. Temperatures in the Cariaco Trench and Gulf of Cariaco.

Depth (m)	*Cariaco Trench*					*Gulf of Cariaco*
	5231 5/XII/55	5269 9/II/55	5606–7 8–9/XI/57	C–349 25/II/58	5683 2/XI/58	1/XI/58
40	25·4	22·7	26·6	22·4	23·3	23·1
50	24·8	21·6	25·2	22·2	22·2	22·2
60	24·2	20·9	24·9	22·0	21·9	20·9
70	23·8	20·6	24·6	21·9	21·6	20·4
80	23·4	20·4	24·4	21·8	21·4	20·4

Table 3. Stability values in the Gulf of Cariaco (Station 5682).

Depth (m)	σ_t, gm l^{-1}	$\Delta\sigma_t$, gm l^{-1}	*Approximate Stability*, m^{-1}
1	24·56		
		0·38	$2·5 \times 10^{-5}$
15	24·94		
		0·15	1×10^{-5}
30	25·09		
		0·20	$1·3 \times 10^{-5}$
45	25·29		
54 (sill depth)		0·52	$3·5 \times 10^{-5}$
60	25·81		
		0·10	$6·7 \times 10^{-6}$
70	25·91		
		0·02	$1·3 \times 10^{-6}$
80	25·93		

It has been suggested that the stability (estimated as numerically, but not dimensionally, equal to $10^{-3}\,\Delta\sigma_t/\Delta D$ where ΔD is the depth difference in metres) across the sill may determine whether or not a basin can become anaeric (RICHARDS and VACCARO, 1956). The stability requirements are not fully established, but RICHARDS and VACCARO's paper implies that values of the order of 10^{-5} m^{-1} are sufficient, while those of the order of 10^{-6} m^{-1} are insufficient for anaeric conditions to develop. In the Gulf of Cariaco, the stability across the sill (Table 3) is sufficiently high to meet the above criterion. Other criteria must also be satisfied for a basin to become anaeric; fundamentally, the rate of supply of organic matter (oxygen consumption) must exceed the rate of ventilation, or supply of oxygenated waters, for some period of time. Thus, in regions where upwelling can insure high rates of organic production, these rates can outstrip circulatory replenishment of oxygen, even in arid regions in low latitudes where evaporation may exceed precipitation, if stability values at sill depth of the order of 10^{-5} are exceeded.

DISSOLVED OXYGEN AND THE APPARENT OXYGEN CONSUMPTION

In Sections I, II and III the surface oxygen concentrations vary but little, between 4·25 and 4·45 ml/l (Fig. 7). All the surface samples were slightly undersaturated, but not greatly so. Values of the apparent oxygen utilization (Fig. 8) in the surface samples were never large enough to indicate the immediate presence of intense *foci*

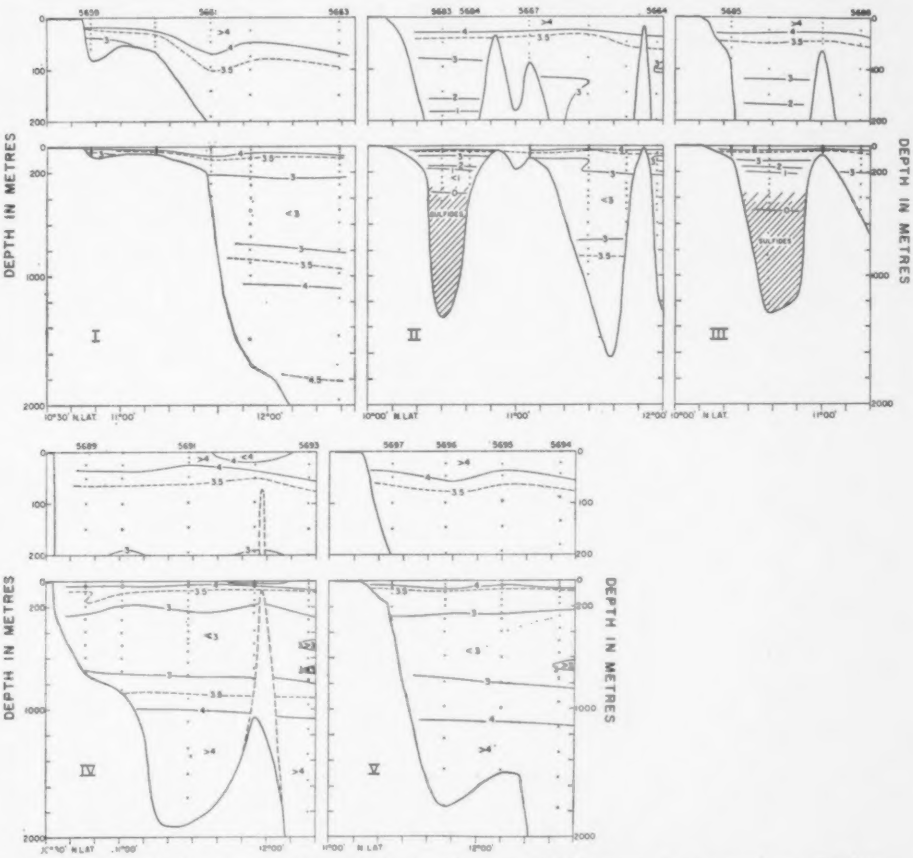

Fig. 7. Dissolved oxygen (ml/l) and the location of sulphide zones in the sections. Station locations are shown in Fig. 1.

of upwelled water and, although it will be developed later that this coast is a region of extensive upwelling, the surface waters were not observed to be far out of equilibrium with the atmosphere. The isopleths of oxygen consumption do, in the upper 100 m, shoal to the southward, and this is taken as an indication of upwelling in the region.

The oxygen minimum layer, containing *ca.* 2·7 ml/l, is found near the σ_t value of approximately 27·1—a value appreciably less than that characterizing the core of the Antarctic Intermediate water, and also less than the values associated with the oxygen minima in the North Atlantic, Pacific, and Indian Oceans, $\sigma_t = 27{\cdot}23$ (see Richards, 1957, p. 204). According to Seiwell (1938), the modal value of σ_t at the

minimum oxygen concentration in the Caribbean is 27·171 ± 0·007 (*sic*), which density occurs at about 500 m in the four sections here considered. The density of the water with which the maximum oxygen consumption is associated appears to be somewhat greater than that at which the minimum oxygen concentrations are found, the former more closely approaching the core of the Antarctic Intermediate water at $\sigma_t = 27{\cdot}36$.

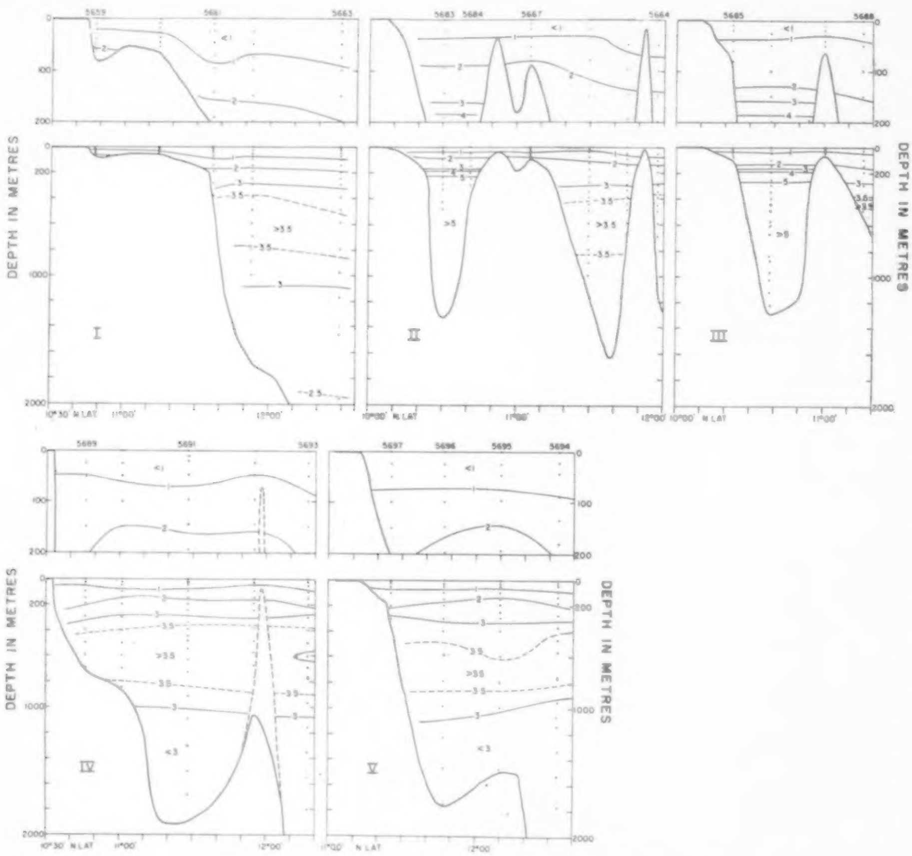

FIG. 8. Apparent oxygen utilization (ml/l) in the sections. Station locations are shown in FIG. 1.

Appreciably unsaturated water reaches the surface at the head of the Gulf of Cariaco, with values of the apparent oxygen utilization as large as 1·18 ml/l at the surface. This appears to be a region of intense, active, rapid upwelling, in which there is an appreciable spatial lag before the water is again oxygenated by contact with the atmosphere, by photosynthesis, or both. However, the observations are more closely spaced here than in the open Caribbean sections, so it is not implicit that the upwelling here is more intense than it may be in correspondingly small areas along the open coast. All the oxygen has been consumed from the water deeper than about 65 m in the Gulf, and sulphide-sulphur concentrations of up to 33 μga/l were observed.

NUTRIENT IONS

Inorganic phosphate, total phosphorus, nitrate and silicate concentrations were observed on Sections I and II (FIG. 9), in the Gulf of Cariaco (FIG. 6), and at Stations 5686 and 5693. The analytical methods were those listed by RICHARDS (1958).

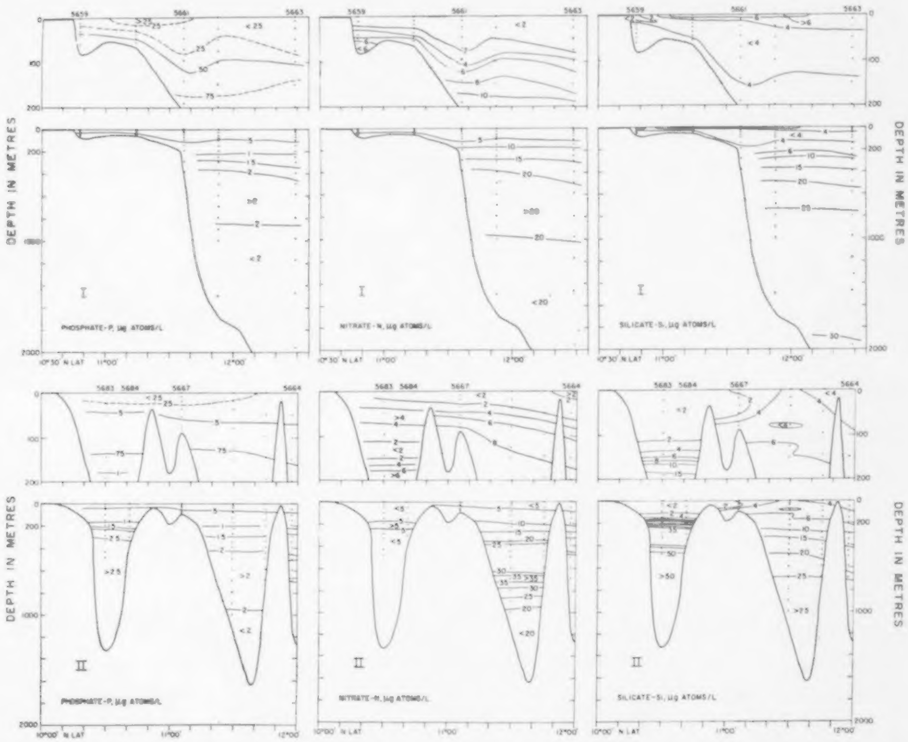

FIG. 9. Distribution of phosphate-phosphorus, nitrate-nitrogen, and silicate-silicon in Sections I and II. Station locations are shown in FIG. 1.

NUTRIENTS IN THE SURFACE, LOW SALINITY WATER

Pursuing the presumption that the surface samples at Stations 5661, 5662 and 5665 have fairly large admixtures of river water, the characteristics of this water can be compared with other, more saline surface water, such as at Stations 5664 and 5667 (Table 4).

The outstanding property of the low-salinity water is its higher silicate content, and, in two of the three cases, high concentrations of organic phosphorus, corresponding to its low phosphate-phosphorus and nitrate-nitrogen contents. The high silicates suggest the presence of silt (or perhaps diatom frustules) in the water, and the low phosphates and nitrates suggest that photosynthetic production of organic matter has stripped the river water of these latter nutrients, prior to or shortly after its entering the Caribbean. The sub-surface distribution of the nutrients in Sections I and II gives no evidence that the low-salinity water is a rich source of nutrients other than silicate.

A major feature of the nutrient distributions in Section I is the upward slope, to the south, of the shallower isopleths between Stations 5660 and 5661. Equal concentrations of nutrients are found at about 50 m at the southernmost of these stations, and at 150 m to the north. This distribution appears to be the consequence of typical upwelling produced by a wind blowing parallel to a coast, with the coast on the left-hand side (SVERDRUP *et al.*, 1946, p. 501, FIG. 124). Similar distributions

Table 4. *Comparison of low-salinity and high-salinity surface samples.*

	Stations				
	5661	5662	5663	5664	5667
Salinity ‰	33·57	33·52	34·57	35·73	36·62
Phosphate–P, μ ga/l	0·28	0·18	0·16	0·35	0·22
Total P μ ga/l	0·32	0·52	0·76	0·36	0·34
Organic P μ ga/l	0·04	0·34	0·60	0·01	0·12
Nitrate-N μ ga/l	0·20	0·10	0·10	3·52	0·60
Silicate-Si μ ga/l	7·20	7·90	5·30	2·80	3·60
Temperature, °C	27·48	27·80	28·06	28·59	25·66

were observed, somewhat less strikingly, in Section II, but this section is topographically more complicated because here the Cariaco Trench is located within the limits of the continental shelf. Thus the upwelled water reaches shallower layers closer to the shore in Section I than it does in Section II, where the major uplift of water occurs along the continental slope north of the Cariaco Trench. (The rise between Stations 5664 and 5665 shown on the diagrams of Section II is the shallow ground surrounding La Blanquilla Island, and does not prevent communication between the waters at Stations 5664 and 5665 both to the east and to the west of the section. However, this feature does appear to initiate the upward flow of waters to the south and southwest).

NUTRIENTS IN THE GULF OF CARIACO

It is apparent from the distribution of nutrients along the length of the Gulf of Cariaco (FIG. 6) that water enters the Gulf at depths between 30 m and the sill depth, about 54 m. The water then rises to the surface layers in the eastern part of the Gulf and enters the photic zone. The westward wind drift carries the surface layer out of the Gulf, but photosynthetic processes rapidly decrease the concentrations of nutrients to low levels. Thus, at the mouth of the Gulf, water flows in at depths greater than about 30 m and simultaneously flows out at shallower depths. This circulation results in marked chemical and physical gradients in the western part of the Gulf, whereas the water column is more homogeneous to the east, where upwelling occurs. The characteristics of the inflowing water, the upwelling water,

and the outflowing water are compared in Table 5. It is apparent that the differences between the nutrient concentrations in the deep, incoming water and in the shallow, outflowing water should closely represent net changes brought about by biological activity within the Gulf. However, the rather large difference in the total phosphorus content of the eastern part of the Gulf and of the western shallow water probably

Table 5. Representative concentrations in water flowing into, upwelling in, and flowing out of the Gulf of Cariaco, and in the anaeric basin.

	Deep, (at mouth)	*East (end)*	*Shallow (at mouth)*	*Anaeric water (of the basin)*
Phosphate-P, μ ga/l	0·5	0·5	0·1–0·2	$>$ 3·3
Total P μ ga/l	0·4–0·5	0·6–0·8	0·3–0·4	$>$ 3·5
Nitrate-N μ ga/l	4	4	0·2	nil
Silicate-Si μ ga/l	2·5–4·0	4	1·2	$>$ 41
Oxygen Consum. ml/l	1·5	1·0–1·5	0·1	Total
Temperature °C	23–24	23–24	25	$<$ 21
Sulphide sulphur, μ ga/l	nil	nil	nil	$>$ 25

represents either conversion into higher forms not captured by the sampling bottles or deposition of phosphorus in sedimentary material, or both. The higher concentrations of total phosphorus in the east (*e.g.*, Stations 5674, 5678, 5679) must come from some source other than the sub-surface inflowing water; the distribution of total phosphorus suggests that some of it is being reissued from the sediments and from the sequestered anaeric water below sill depth.

The anaeric waters of the deepest part of the Gulf (Table 5) comprise a special case of nutrient entrapment, with concentrations which are extraordinarily high in comparison with freely circulating aerated ocean waters at comparable depths.

MAGNITUDE AND EXTENT OF UPWELLING IN THE REGION

In regions of coastal upwelling, the transport of nutrients into the euphotic zone occurs *across* the geostrophic flow, which is a longshore current in this region (see the distribution of density, FIG. 4). Criteria other than the dynamic topography must, therefore, be used in order to estimate the magnitude of upwelling and its accompanying transport of nutrients. The calculations which follow are an attempt to make such an estimate; they are presented primarily to suggest a method by which such transports might be estimated, even though the present treatment may not be fully borne out by the data from any single cruise. In particular, it will be assumed that our Section II and the *Crawford* section of February 1951 were simultaneous, or rather that similar conditions prevailed at these two times. However, the results are interesting in themselves and are consistent with the other estimates of biological productivity in the region.

The cross-current transport estimate depends on the magnitude of the northward transport of surface waters due to the winds. Estimates of these northward transports

have been made by MONTGOMERY (1936) and by BROOKS (1939), using MONTGOMERY's methods. They calculate, from average pressure distributions, that in this region (10°–15°N, 60°–65°W) there is a nearly northward transport of surface water of 2·97 tons/m/sec in July (MONTGOMERY) and of 2·06 in January (BROOKS). These estimates apply to some offshore region theoretically uninfluenced by the coast. BROOKS further states that the drift current is essentially limited to a surface homogeneous layer usually less than 50 m thick.

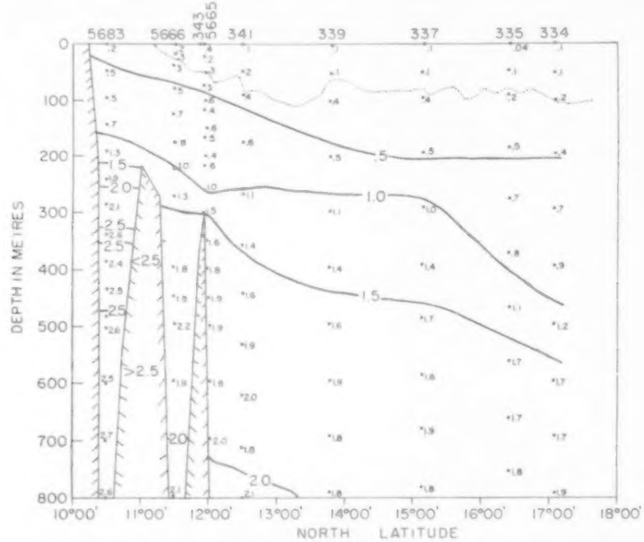

FIG. 10. Distribution of inorganic phosphate (μ ga/l) along a composite section from Section II (see FIG. 1) and the *Crawford* section of February, 1958. The upper dotted line shows the bottom of the upper isothermal layer, determined from the bathythermograph record made on the *Crawford* section.

It will be assumed that BROOKS' estimate for the northward volume transport in January applies and is achieved at *Crawford* Station 341 and northwards. From inspection of Sections I and II, the *Crawford* section, and the distribution of inorganic phosphate along a composite section made up of Section II and the *Crawford* section (FIG. 10) the following conditions will be assumed :

1. The northward transport estimated by BROOKS is confined to the upper mixed layer, which will be assumed to be 90 m thick at and north of *Crawford* Station 341 (the actual thickness of this layer is shown by the bathythermograph record of the thickness of the isothermal surface layer, FIGS. 4 and 10). This water has the average chemical charatceristics

$$S = 35{\cdot}8‰$$

$$PO_4^{-3} - P = 0{\cdot}1\ \mu\ \text{ga/l}$$

$$\textit{Silicate-Si} = 4\ \mu\ \text{ga/l}.$$

2. The northward flowing water in the upper 90 m consists of a mixture of : (a) waters which upwell in the region south of Station 341 from between the

isentropic surfaces where $\sigma_t = 24$ (near the bottom of the mixed surface layer) and $\sigma_t = 26$; and (b) lower salinity surface water from the east. The upwelling water has the volume transport V_u and the average chemical characteristics

$$S = 36{\cdot}5‰$$

$$PO_4^{-3} - P = 0{\cdot}45\ \mu\ \text{ga/l}$$

$$Silicate\text{-}Si = 1{\cdot}0\ \mu\ \text{ga/l}$$

(It will be noted that the silicate concentrations at the north end of Section II, between $\sigma_t = 24$ and 26, are appreciably higher than 1 μ ga/l. However, they would be reduced by biological activity to about 1 μ ga/l upon rising, south of Station 341, into the euphotic zone so that the upwelling water, rising to mix with surface water, would ultimately have about this concentration).

3. The surface waters from the east which mix with the upwelled water have the volume transport V_e, an unknown salinity S_e, and the average chemical characteristics

$$PO_4^{-3} - P = 0{\cdot}1\ \mu\ \text{ga/l}$$

$$Silicate\text{-}Si = 7\ \mu\ \text{ga/l}$$

4. The silicate in the surface water from the east is considered to be conservative, because nitrate concentrations appear to be too low to support further photosynthesis in the surface layer.

It is desirable to introduce silicates into the discussion because the surface, low-salinity water is particularly high in silicate, enabling it to be traced. Phosphate, on the other hand, is low both in this water and in the mixed water flowing northward along Section II. Silicate is thus distinctive. In addition, it is difficult to know what average value to assign to the salinity of the upper layer of Section I, with the result that S_e and V_e are unknown.

With the above assumptions, it is possible to estimate both the amount of upwelled water and the biological consumption of phosphorus from that water, and still maintain a balance of salt in the model :

$$V_u + V_e = 2{\cdot}06 \text{ ton/m/sec (volume balance)}$$

$$V_u \times 36{\cdot}5 + V_e S_e = 2{\cdot}06 \times 35{\cdot}8 \text{ (salt balance)}$$

$$V_u \times 1 + V_e \times 7 = 2{\cdot}06 \times 4 \text{ (silicate balance)}$$

Solving,

$$V_u = 1{\cdot}03 \text{ tons/m/sec}$$

$$V_e = 1{\cdot}03 \text{ tons/m/sec}$$

$$S_e = 35{\cdot}09‰$$

The model can be used to compute the biological productivity induced along the coast by the upwelling, from the conversion of the inorganic phosphate into organic matter *via* photosynthesis, as follows :

North of *Crawford* Station 341, the surface layer contains approximately 0·1 μ ga $PO_4^{-3} - P$/l, *i.e.*, 0·35 μ ga/l of the phosphate-phosphorus originally present

in the upwelled water has been converted into organic matter by the time the upwelled water is 150 miles ($2\cdot78 \times 10^5$ metres) offshore. Therefore, in a strip one metre wide extending 150 miles seaward, the conversion of phosphorus is, for each square metre per day ($8\cdot6 \times 10^4$ seconds)

$$\frac{8\cdot6 \times 10^4 \times 1\cdot03 \times 10^3 \times 0\cdot35}{2\cdot78 \times 10^5} = 111\ \mu\text{ ga } PO_4^{-3} - \text{P/m}^2\text{/day.}$$

The photosynthetic conversion of this amount of phosphorus is equivalent to the production of 0·14 gm of organic carbon/m²/day (FLEMING, 1940).

The only tests of the model lie in the independent estimates of productivity which have been made in this region, and in the value of $S_e = 35\cdot09‰$, which is not unreasonable. The productivity estimate is somewhat less than that of 0·48 gm C/m²/day made by RYTHER (RICHARDS and VACCARO, 1956) from carbon[14] determinations of photosynthetic rates. Estimates made by CURL (1960) along this section during *Atlantis* Cruise 246, using the method of RYTHER and YENTSCH (1957), were 0·32, 1·40 and 0·78 gm C/m²/day; these estimates represent gross photosynthesis, while the change in phosphate should more nearly represent net productivity.

A similar estimate of an organic production rate can be made from the phosphate and hydrographic data in the Gulf of Cariaco. The estimate of the outward wind drift of the surface water is based on the navigational record of the ship's drift on stations. The distributions of density and phosphate (FIG. 6) indicate that water containing $0\cdot5\ \mu$ ga $PO_4^{-3} - P/1$ upwells in the area between Station 5674 and the head of the Gulf, and that between Stations 5674 and 5682 there is a decrease in phosphate-phosphorus of *ca.* $0\cdot35\ \mu$ ga/l. The outward drift of water is at a speed of about one knot, and in a distance of 4 to 8 miles (4 to 8 hours), $0\cdot15\ \mu$ ga/l of phosphate-phosphorus is photosynthetically converted to organic matter. The euphotic zone here is about 10 m deep, so in it $0\cdot15 \times 10^3 \times 10\ \mu$ ga P is fixed in 4 to 8 hours under each square metre, i.e., 1·5 mga or 46·5 mg P/m²/4–8 hours. If the photosynthetic period per day is 12 hours, the daily production of organic carbon would be *ca.* 2·8 to 5·7 gm/m². CURL (1960) made two estimates of productivity in the Gulf: one of 0·52 gm C/m²/day at the head of the Gulf, and one of 3·8 gm C/m²/day near Station 5670.

The distribution of salinity, temperature, and dissolved oxygen along *Atlantis* Sections I to V and along the February 1958 *Crawford* section indicate that the degree of upwelling decreases toward the west, and although there is some suggestion of upwelling in Section IV there is scarcely any trace of it in the observations along Section V.

SUMMARY AND CONCLUSIONS

These Venezuelan coastal waters are of two main sources, as described by PARR (1937a). The first is a contribution from the western Sargasso Sea which intrudes, as a salinity maximum in the upper 200 m, both under and over water from the second source, water of equatorial Atlantic origin which enters the Caribbean through southern Antillean channels. The latter water contains an accretion of lower-salinity Antarctic Intermediate water, which is evident as a salinity minimum at 700 to 800 m. A third superficial low-salinity component, of South American river and/or equatorial Atlantic origin, may be present to a greater or lesser extent, varying with the season and, in turn, with fluctuations in the outfall of the Orinoco and Amazon Rivers.

This coast is a region of high biological productivity which results from the upwelling of water (from depths of some 90 to 160 m, 150 km offshore) into the inshore surface layers, a process which introduces water containing *ca.* 0·45 μ ga/l of inorganic phosphate-phosphorus and *ca.* 6 μ ga/l of inorganic nitrate-nitrogen into the euphotic zone, where these nutrients sustain the photosynthetic production of organic matter. This transport has been estimated to result in an average net production of 0·14 grams of organic carbon per m^2 per day in a region extending 150 km offshore.

A study of the Gulf of Cariaco shows that it, too, is a region of upwelling and relatively high biological productivity. The waters in the Gulf at depths greater than the sill depth are sufficiently colder and denser than the overlying waters that they do not exchange and have become stagnant. They contain no oxygen and have large concentrations of sulphides, phosphates and silicates. A consideration of the distribution of temperature outside the Gulf indicates the possibility that this deep water may be replaced in February, either annually or intermittently.

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Primary production measurements in the north coastal waters of South America

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Abstract—Measurements of surface light intensity, water transparency and concentration of chlorophyll *a* were made in the northern coastal waters of South America during October and November 1958. Phytoplankton collections were made simultaneously. The highest gross production rates were encountered in the Gulf of Cariaco (3·75 g C/m^2/day), over the Cariaco Trench (2·30 g C/m^2/day), in Lake Maracaibo (1·23 g C/m^2/day) and the Gulf of Venezuela (1·20 g C/m^2/day). Upwelling appears to be the source of nutrients for production in the Gulfs of Cariaco and Venezuela. This relationship is less well established over the Cariaco Trench. High silt concentrations limit light for photosynthetic production in the Gulf of Darien, at the mouth of the Magdalena River and to the east of Margarita Island. Phytoplankton reduces materially the light available for photosynthesis in Lake Maracaibo.

INTRODUCTION

THE MEASUREMENT of primary production rates may be used to confirm our understanding of physical, chemical and biological phenomena, to delimit areas where observations on such phenomena should be undertaken and to complement marine deposition studies. Such measurements are interesting in their own right since they indicate the base on which successively higher trophic levels may build.

In the region being considered there has been only one estimation of primary production (RYTHER, *vide infra*), using the C^{14} method. However, many indications of very high productivity (flocks of fish-eating birds, large catches of ' herring ' by hand seining in the Gulf of Cariaco, sightings of schools of scombrids, etc). are present in a number of localities on the northern coast.

The present data were obtained on Cruise 246 of the R. V. *Atlantis* during October through November, 1958 from Trinidad, B. W. I. to the Gulf of Darien, Columbia. This coast line and its geography have been described extremely well by MURPHY (1936).

For our purpose it is sufficient to divide the coastal waters (FIG. 1) into four separate regions :

(1) Trinidad to the Paraguana Peninsula, including the Gulf of Cariaco and the Cariaco Trench, under the influence of the Equatorial Current flowing from east to west and the Northeast Tradewinds.

(2) Lake Maracaibo, which is fed by orographic rainfall to the south and flushes very slowly, and the Gulf of Venezuela with upwelling taking place on its eastern side.

(3) The region from the Goajira Peninsula to the mouth of the Magdalena River, which is poorly known. Water from the Magdalena River appears to flow northeast toward the Goajira Peninsula in accordance with the Coriolis principle and thence northwestward.

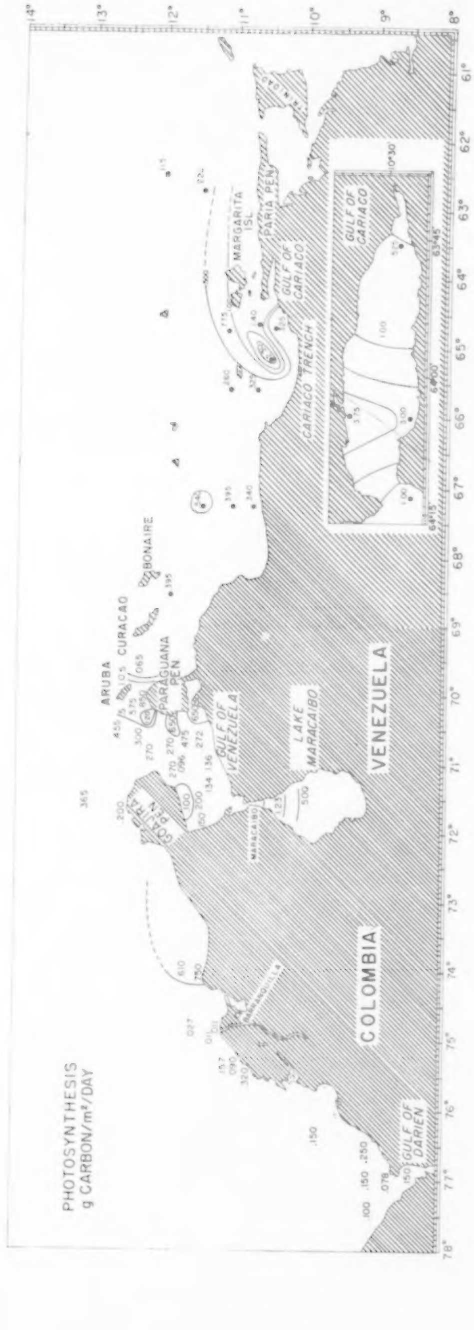

FIG. 1. Primary production between Trinidad, B.W.I. and Gulf of Darien, Columbia, expressed as *g* Carbon/m²/day.

(4) The Gulf of Darien region, which is probably the centre of an eddy and is even less well known than the preceding region.

Discussions of the hydrography of one or more of the regions may be found in PARR (1937), RAKESTRAW and SMITH (1937), DIETRICH (1939), REDFIELD and KETCHUM (1953), REDFIELD (1955), REDFIELD, KETCHUM and BUMPUS (1955), WORTHINGTON (1955, 1956) and RICHARDS (1960).

METHODS

Plankton tows and water samples for chlorophyll *a* analysis were taken in conjunction with hydrographic and geological observations. Tows were made with nets of number 10 nylon and preserved in neutralized ten per cent formalin. Aliquots have been analyzed for chemical composition and will be reported elsewhere. Water samples were taken with samplers coated with a non-toxic, non-dissolving plastic.

One or more litres of water were filtered through HA ' Millipore ' membrane filters and the filters stored in a refrigerated dessicator. Chlorophyll *a* determinations were made on the filtered material ashore according to the method of CREITZ and RICHARDS (1955). Light intensity measurements were made with a General Electric exposure meter and light penetration measurements were made with a Secchi disc. Average light values were taken from KIMBALL'S (1928) tables.

Phytoplankton production estimates were made according to the method of RYTHER and YENTSCH (1957) using chlorophyll and light data. As pointed out by these authors the method measures ' average ' production. Criticism of the method centres about interpreting variation in the coefficient of light saturated photosynthesis to chlorophyll (VERDUIN, 1959). The interpretations of the present data assume that variations in the chlorophyll-photosynthesis ratio are real and not due to experimental error, and that such variations differ from the mean by a factor of two or less while the measured parameters may vary by more than an order of magnitude.

Table 1. Total Chlorophyll a *in the euphotic zone and depth of the euphotic zone by stations. Refer to* RICHARDS (1960, Fig. 1) *for geographic locations of stations. Euphotic depth is the depth to which one per cent of the surface light penetrates as calculated from* SECCHI *disc measurements.*

Station	*Euphotic depth* (m)	*Chl.* a mg/m^2	*Station*	*Euphotic depth* (m)	*Chl.* a mg/m^2
5661	43	10·3	5722	9	7·9
5664	43	8·0	5725	12	7·6
5667	31	38·0	5726	25	20·0
5678	25	24·0	5727	25	29·0
5683	54	20·0	5732	10	170·0
5684	50	230·0	5733	85	18·0
5686	56	21·0	5735	15	12·0
5687	43	15·3	5736	85	34·0
5697	37	6·3	5740	3	1·0
5698	36	40·0	5741	3	0·9
5699	36	37·0	5742	10	2.0
5700	62	63·0	5743	54	4·0
5701	50	15·0	5750	35	6·0
5704	52	33·0	5751	22	4·0
5710	34	19·0	5752	10	9·0
5715	27	13·5			

RESULTS

The euphotic depths varied from 30 metres in the Gulf of Cariaco and to the west of Margarita Island to 85 metres in the vicinity of Curaçao (Table 1). The contours of the isopleths suggest a westward movement of the surface water, with

decreasing turbidity to the west. The shallow light penetration at the mouth of the Gulf of Cariaco was accompanied by a high standing crop of phytoplankton (200×10^3 cells per litre). The shallow light penetration between Margarita Island and Tortuga Island was obviously due to silt but whether of local origin or from mixing with Orinoco River water is not certain. Vertical mixing was impeded by the large vertical thermal gradient but relatively low salinities indicated some admixture of coastal water (RICHARDS, 1960).

Calculated phostosynthetic rates in this area (FIG. 1) ranged from a low of 0·115 g C/m²/day to the west of Grenada to 3·75 g C/m²/day on the north shore of the Gulf of Cariaco. The second highest production rate occurred over the south central portion of the Cariaco Trench (2·30 g C/m²/day). The configuration of the isopleths form a tongue extending from Margarita southwestward to over the trench.

Light penetrates the least in northern Lake Maracaibo as a result of high standing crops of phytoplankton ($1{\cdot}5 \times 10^6$ cells per litre) and in the southern portion of the Gulf of Venezuela as a result of silt suspension. The deepest light penetration occurs on the eastern side of the Gulf. Relatively high photosynthetic rates were found in the eastern portion of the Gulf of Venezuela and in the vicinity of Aruba. The highest rates were found in the northern end of Lake Maracaibo (1·23 g C/m²/day) and off the Paraguana Peninsula (1·20 g C/m²/day) (FIG. 1). In this region the lowest rates of production were associated with the most turbid water.

Both the transparency and the production from the western waters are a reflection of the Magdalena River flow, which was beginning to increase in November. The lowest transparency and production rates along the entire coast were found at the mouth of the Magdalena River. The euphotic depth isopleths are crowded to the west of the river mouth and expanded to the east, suggesting an eastward flow of the surface waters. The production isopleths indicate low rates to the west in clear water, and relatively high rates (0·750 g C/m²/day) in equally clear water to the east presumably as a result of admixture with nutrient rich river water.

The last region shows no unusual features and appears to be relatively unproductive (*ca.* 0·150 g C/m²/day).

For comparison with other areas, STEEMANN NIELSEN (1959) gives a typical primary production rate of 0·050 g C/m²/day in the centre of tropical anticyclonic eddies and a rate of 0·50 g C/m²/day in other parts of the tropical oceans. On the continental shelf area off New York, RYTHER and YENTSCH (1958) found between 0·10 and 0·60 g C/m²/day fixation as monthly averages, with extremes values of zero and 2·8 g C/m²/day.

DISCUSSION

It has been shown that there are at least four areas of high basic productivity on the northern coast of South America. The high productivity over the Gulf of Cariaco is probably due partly to upwelling (RICHARDS, 1960) and partly to nutrient supply in surface coastal waters. Upwelling is strong to the east of Margarita but the turbidity of the water prevents any substantial photosynthesis until some of the suspended matter has an opportunity to settle out in the still waters over the trench. Unpublished work by D. S. SHONTING (FIG. 2) in 1957 shows the magnitude of this phenomenon. Using a white light source and a photomultiplier photometer, SHONTING measured the 90° scattering by particles at four stations. His figures show the distri-

bution of light scattering particles in the Cariaco Trench. Apparently one third of the original sediment load settles out in the shallow eastern basin and another third settles out in the central basin.

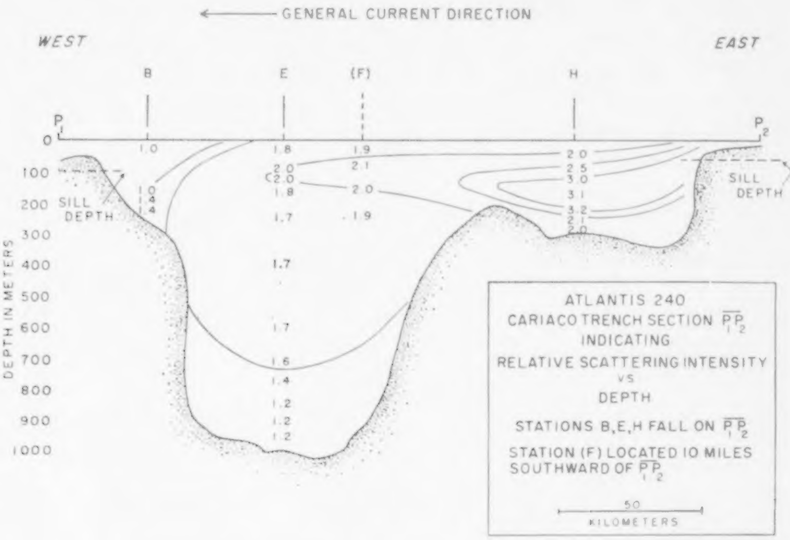

FIG. 2. Intensity of relative scattering (90°) by white light in the Cariaco Trench plotted against depth. (From unpublished data of D. S. SHONTING).

According to data presented by RICHARDS in a comparison of high and low salinity surface water in the Cariaco Trench region, there was virtually no difference in dissolved phosphorus but considerably higher silicate and lower nitrate in the low salinity water. The low salinity water has much higher concentrations of organic phosphorus and total phosphorus indicating that it is a potentially richer source of these nutrients but that they have been used up in producing organic matter. RICHARDS estimated the amount of net production taking place in a north-south section in the eastern Cariaco Trench region from upwelling rates deduced by BROOKS (1939) and the north-south differences in phosphate–phosphorus concentrations. The computed rate of net production was 0·14 g C/m^2/day. In the same area RYTHER (cited in part in RICHARDS and VACCARO (1956) and in part unpublished), using the C^{14} method made productivity measurements in 1955 ranging from 0·27 to 0·48 g C/m^2/day, (Table 2).

The C^{14} measurements, under an assumed nutrient sufficiency, represent net photosynthesis, whereas the chlorophyll-light estimates represent gross photosynthesis. The ratio of net to gross photosynthesis is in the vicinity of 0·9 in a normal population in the logarithmic growth phase. This may reduce to zero if the population is making no net growth whatsoever (RYTHER and YENTSCH, 1958; KETCHUM *et al.*, 1958). A ratio of 0·1 over the central basin of the trench suggests that the observation was made at the end of a plankton bloom, inasmuch as the phytoplankton standing crop was large.

The waters flowing over the Cariaco Trench from east to west become clearer and less productive. The trench itself is thus an ideal location as a trap for organic material formed in its proximity.

In the Gulf of Cariaco RICHARDS (1960) has made a strong case for upwelling at the eastern end. The surface water flows westward half the length of the Gulf before maximum rates of production are achieved.

Table 2. Comparison of primary productivity measurements in the eastern surface waters of the Cariaco Trench by three methods: C^{14} *(net), phosphate-phosphorus depletion (net) and chlorophyll-light (gross).*

Location	RYTHER (1955) C^{14} (net)	RICHARDS (1958) PO_4–P *depletion (net)* g C/m²/day	CURL (1959) *Chlorophyll a-light (gross)*
Caribbean	0·27	—	
Cariaco Shelf	0·35	—	0·78
Cariaco Trench	0·48	0·14	1·40
Southern Edge	—	—	0·32

Lake Maracaibo is relatively rich in phosphorus and presumably in other nutrients (REDFIELD *et al.*, 1955). At the time of our visit there was a very high standing crop of phytoplankton. In October 1952 GESSNER (1956) found an average of 6×10^6 cells per litre, mostly *Microcystis* and *Lyngbya*. In 1958 there was almost no silt in the water but the water transparency was low due to the plankton population itself. Consequently the calculated production was low.

In the Gulf of Venezuela the wind pattern appears to control basic production. The water on the western side is roiled and supports a low standing crop. There is evidence for weak upwelling on the eastern side (REDFIELD, 1955) and production rates are fairly high in a number of non-contiguous localities. In contrast to the Gulf of Cariaco, the Cariaco Trench and Lake Maracaibo, all of which have poorly ventilated basins and the deep water more or less anaerobic, the Gulf of Venezuela is open to the sea and undergoes at least seasonal flushing. Thus, there is virtually no accumulation of organic matter in the sediments along the eastern shore (W. ATHEARN, personal communication). However, the basin of Calabozo Bay (the southwestern portion of the Gulf) has an organic-rich sediment (J. ZEIGLER, personal communication) due in part to trapping material formed in Lake Maracaibo (REDFIELD, 1955) and to *in situ* production on the south coast of the Goajira Peninsula.

During November 1958 the main flow of the Magdalena River could be traced to the northeast. The light and photosynthesis data indicate that as the water cleared production increased. Unfortunately we have no data for the waters just to the west of the Goajira Peninsula. This would appear to be an ideal coast for upwelling as deep water is close inshore and the prevailing winds are unimpeded by physiographic features.

In the Gulf of Darien and surrounding waters, currents and general circulation are not known well enough to permit interpretation of the present data. If the waters remain turbid throughout the year there is little likelihood of much organic production.

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A note on water movement in the Greenland–Norwegian Sea

WILLIAM G. METCALF

(*Received* 28 *September* 1959)

Abstract—The oceanography of the Greenland–Norwegian Sea which was described by Norwegian oceanographers in the early part of the present century is reviewed in the light of recent winter data.

The dynamic topography and two-hundred metre temperatures indicate a circulation generally similar to that given in the earlier descriptions except that the cyclonic movement in the Norwegian Sea appears to be further west and the Norwegian Current appears to be much broader than it was previously considered to be.

Deep water identical to that of the Norwegian Sea and appreciably warmer than that of the Greenland gyral core lies on at least three sides of that gyral, and it is suggested that this is the major source of Polar Basin deep-water. It is probably formed within the Norwegian gyral. Deep-water in the Greenland–Norwegian Sea may not be formed each winter but only during particularly cold seasons. Deep-water which is formed within the Greenland gyral eventually loses its cold identity through gradual mixing with the surrounding water from the Norwegian gyral.

A temperature–depth diagram demonstrates two distinct types of intermediate and deep-water as well as two groups of stations showing some of the charateristics of each type within a single water column. Bottom topography is believed to play a significant role in the distribution of this type of station.

Further field studies, especially in the western part of the Greenland Sea, are needed to fill the large gaps in our knowledge of the circulation pattern.

INTRODUCTION

THE oceanography of the area between Norway and Greenland was the object of intensive study during the early part of the present century resulting in very thorough descriptions especially by NANSEN (1906) and HELLAND-HANSEN and NANSEN (1909). A great part of our knowledge today of this region is the result of the work of these investigators. The present paper is based upon winter oceanographic data gathered from 1951 to 1955, inclusive, which may clarify and modify some of the earlier work.

The geographical terminology of the region has undergone numerous changes in the past fifty years, and it is felt that in order to reduce the confusion as much as possible, the terms used in this paper should be defined. The region as a whole (FIG. 1) bounded on the north by the passage between Svalbard and Greenland and on the south by the Greenland–Iceland–Faroe–Shetland Ridge, is referred to as the Greenland–Norwegian Sea.* The portion of the area north of Jan Mayen Island and of the East and West Jan Mayen Ridges, is termed the Greenland Sea; that to the south the Norwegian Sea. The Norwegian Sea is divided by the Iceland–Jan Mayen Ridge into the Norwegian Basin on the east and the Iceland Basin on the west. Similarly, the Greenland Sea is divided by the North Jan Mayen Ridge into the large Greenland Basin occupying most of that sea and the smaller Jan Mayen Basin

* FIG. 1 shows an east–west ridge, the Nansen Ridge, extending between Svalbard and Greenland, and this was formerly considered to be the northern boundary of the region under discussion. However recent evidence reveals a relatively deep passage through this supposed ridge thus forming a connection between the Greenland–Norwegian Sea and the Polar Basin at depths as great as 3000 or 3500 m (BALAKSHIN, 1959).

in the south-west corner. The eastern boundary of the Greenland–Norwegian Sea is Norway, the shallow Barents Sea and Svalbard. Greenland forms the entire western side.

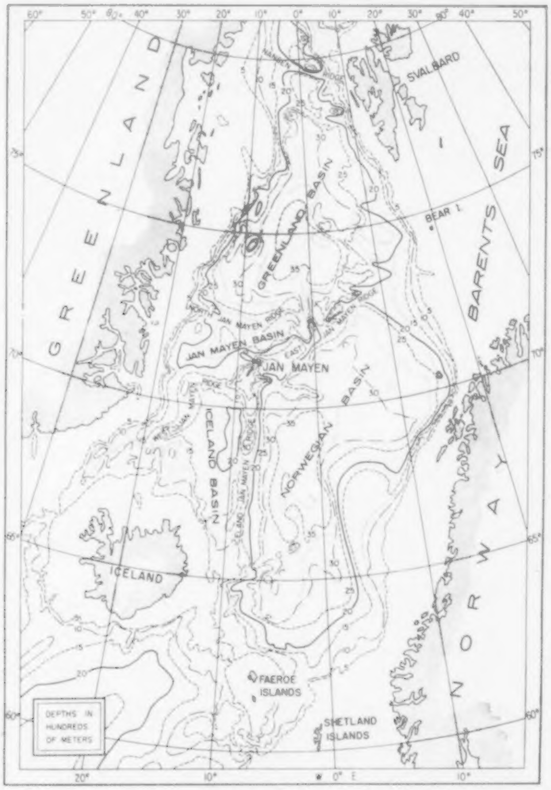

FIG. 1. Bathymetry of the Greenland–Norwegian Sea (after STOCKS 1950).
Note : The existence of a channel with depths of 3000 m or greater extending north–south through the Nansen Ridge has recently been described (BELAKSHIN, 1959 and LAKTIONOV, 1959).

CIRCULATION

HELLAND-HANSEN and NANSEN (1909) described the circulation of the Greenland–Norwegian Sea as being composed of two major cyclonic gyrals, one in the Norwegian Sea and one in the Greenland Sea, together with a number of smaller permanent, semi-permanent and transitory vortices. In addition, they described the warm north-flowing Norwegian Current on the east, the cold south-flowing East Greenland Polar Current on the west, and several smaller currents. Their schematic representation of this circulation is well known and has been generally accepted as being reasonably accurate (FIG. 2).

The purpose of the present paper is to discuss some of the recent winter oceanographic observations made in this region between 1951 and 1955 inclusive and to compare the recent results with the earlier work. The recent material substantiates to a considerable degree the earlier conclusions and emphasizes a rather out-standing

separation between the two major cyclonic movements. For convenience, the southern cyclonic circulation will be called the Norwegian gyral and the northern one the Greenland gyral.

FIG. 3 represents the dynamic topography of the area as determined by the dynamic height anomalies based on the 1500 decibar surface. This level was chosen simply because of the availability of the data to that depth. Many of the hydrographic stations did not extend deeper. Approximately sixty stations were used in the calculations. These scattered over an area the size of the Greenland–Norwegian Sea can,

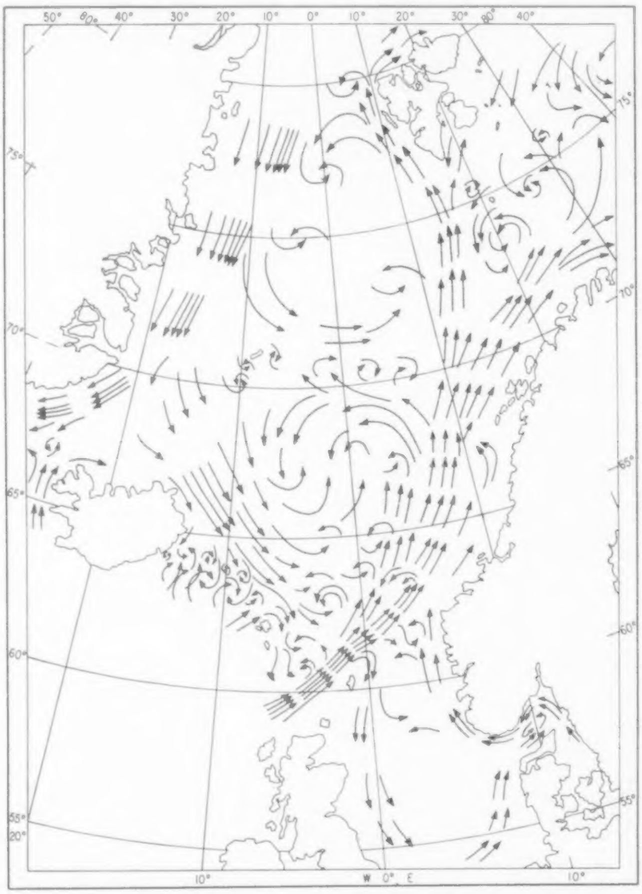

FIG. 2. Surface currents of the Greenland–Norwegian Sea (after HELLAND-HANSEN and NANSEN, 1909).

of course, give little more than a hint of the situation, and undoubtedly the contours could have been drawn in many different ways. The observations were gathered in connection with five different cruises in four different winters, and it is to be expected that certain irregularities would appear due to annual variations in current positions from year to year and unavoidable inaccuracies in navigation. Therefore, in drawing the contours for FIG. 3, a small amount of smoothing of the lines and averaging of

the data was carried out in order to produce what is felt to be a picture of average conditions.

In a comparison between the HELLAND-HANSEN and NANSEN interpretation and the present one, a difference in the position of the Norwegian gyral is apparent. In the earlier chart, it was shown centred on a line running approximately between the Faroe Islands and southern Svalbard; the more recent data indicate that it lies considerably west of that position, centred on a line extending between Iceland and Jan Mayen Island. The north-flowing Norwegian current is shown to be very much broader than previously described. The Norwegian gyral is thus restricted for the most part to the Iceland Basin, extending only slightly east of the Iceland–Jan Mayen Ridge into the Norwegian Basin. The many small vortices and vagaries of the currents shown throughout the region in the HELLAND–HANSEN and NANSEN chart do not appear in the present one. The averaging of the data for several years smooths out this type of current structure. However it is likely that many such smaller currents and eddies are present at any given time.

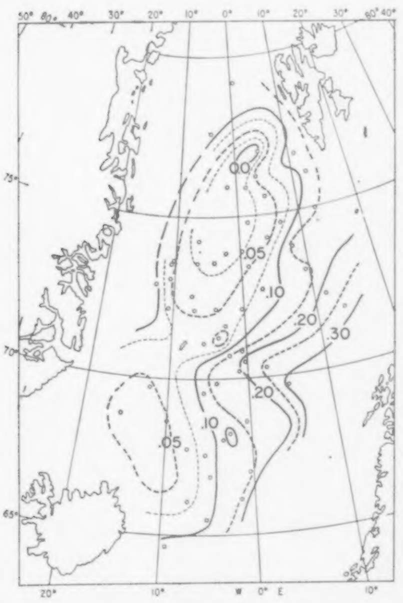

FIG. 3. Geopotential topography of the sea surface relative to the 1500 decibar surface. Composite of data from four winters, 1951–1955 inclusive.

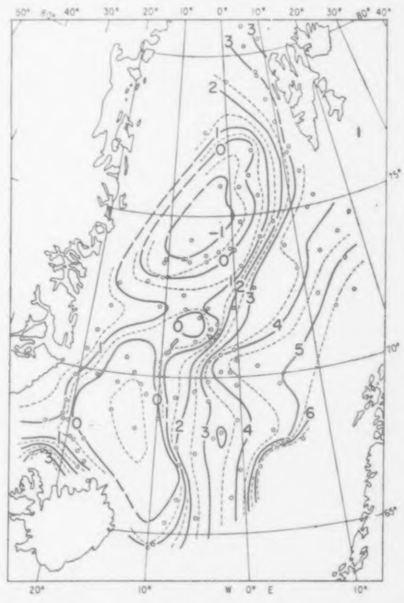

FIG. 4. Two-hundred metre temperatures of the Greenland–Norwegian Sea. Composite of data from four winters, 1951–1955 inclusive.

FUGLISTER (1954) has demonstrated that in the North Atlantic Ocean, gradients in the 200 metre temperature are associated with the average current pattern. A 200 metre temperature chart (FIG. 4) of the Greenland–Norwegian Sea based upon the recent winter data was drawn from the data of over 130 stations occupied during four different winters. As was the case in connection with the previous figure, certain inconsistencies were found due to the non-synoptic character of the data. Again, a small amount of averaging of the data and smoothing of the contours was carried

out to produce what is considered to be an average picture. The 200 metre temperature contours as well as the dynamic topography emphasize the position of the Norwegian gyral in the western half of the Norwegian Sea and a very broad Norwegian Current extending over the whole eastern half of that sea.

The East Jan Mayen Ridge is shown by STOCKS (1950) to rise to within about 600 metres of the sea surface in some places. Depths of greater than 2000 metres are shown in a narrow passage between two high peaks, and at the eastern end of the ridge the depths are between 1500 and 2000 metres. As the Norwegian Current approaches this ridge, some of the water it carries is diverted to the west as part of the Norwegian gyral while the rest flows northeast. This latter portion then flows around the eastern side of the Greenland gyral, and some of the water from the upper levels enters the Polar Basin slightly below the sea surface between Greenland and Svalbard. The remaining portion appears to continue in a cyclonic direction as the outer margin of the Greenland gyral.

Table 1. Two stations in the cold core of the Greenland gyral including the coldest one in the present data.

Depth (m)	*Temp.* (°C)	*Salinity* (‰)	*Oxygen* (ml/L)
Station No. 38. 18 *March* 1955. 75° 52′ *N.*, 01° 46′ *W.* *Depth* 3840 *m.*			
1	− 1·61	34·87	8·18
45	− 1·67	34·87	8·15
90	− 1·62	34·87	8·11
181	− 1·18	34·90	7·73
370	− 1·30	34·89	7·72
565	− 1·23	34·89	7·73
878	− 1·20	34·90	7·72
1332	− 1·08	34·91	7·42
1794	− 1·06	34·92	7·47
2265	− 1.06	34·91	7·39
2745	− 1·06	34·91	7·43
3241	− 1·06	34·90	7·39
Station No. 39. 18 *March* 1955. 74° 15′ *N.*, 06° 38′ *W.* *Depth* 3330 *m.*			
1	− 1·58	34·87	8·17
48	− 1·64	34·86	7·91
96	− 1·59	34·86	7·85
194	− 1·00	34·91	8·00
392	− 1·13	34·90	7·56
596	− 1·24	34·90	7·61
799	− 0·95	34·92	7·63
1269	− 1·09	34·92	7·60
1759	− 1·06	34·92	7·39
2252	− 1·06	34·91	7·56
2747	− 1·07	34·92	7·75
3243	− 1·05	34·95	7·41

THE DEEP-WATER

The term deep-water is used here to indicate water below 1500 metres where the temperature and salinity are relatively constant. In the recent data, the deep-water in the core of the Greenland gyral is shown to be − 1·00° or colder with a single exception (− 0·99°). That of the Norwegian sea is − 0·97° or warmer without exception (Tables 1 and 2). However, this less cold deep-water is also found on the east,

north and northwest borders of the Greenland gyral (Table 3). Whether or not it is present along the west side has not been determined due to ice conditions which precluded field work on that side, but conditions along the southwest side of the gyral suggest that it is. It thus appears that deep-water from the Norwegian Sea is carried by the Norwegian Current either through a gap in the East Jan Mayen Ridge or around the end of that ridge, or more likely both, and takes a position around the edges of the cyclonic eddy in the Greenland Sea.

Table 2. Two typical Norwegian Sea stations.

Depth (m)	*Temp.* (°C)	*Salinity* (‰)	*Oxygen* (ml/L)
Station No. 25. 10 *February* 1954. 65° 33′ *N.*, 05° 18′ *W.* *Depth* 2743 *m.*			
1	2·71	34·90	7·69
10	2·70	34·89	7·72
30	2·69	34·98	7·74
50	2·68	34·88	7·65
100	2·79	34·90	7·69
200	2·37	35·04	7·49
396	0·83	34·96	7·43
792	− 0·51	34·92	7·36
1188	− 0·78	34·91	7·09
1585	− 0·95	34·92	7·16
1980	− 0·93	34·92	7·15
2475	− 0·93	34·95	7·13
Station No. 5. 5 *March* 1955. 69° 15′ *N.*, 13° 00′ *E.* *Depth* 2926 *m.*			
1	5·95	35·03	6·79
40	6·07	35·15	6·70
80	—	35·15	6·74
162	6·12	35·17	6·71
332	4·91	35·09	6·81
509	2·25	34·99	6·96
627	0·66	34·94	7·06
856	− 0·37	34·93	6·98
1092	− 0·72	34·93	7·09
1504	− 0·89	34·92	6·92
1942	− 0·90	34·91	6·93
2406	− 0·92	34·91	6·94

NANSEN (1906) and HELLAND-HANSEN and NANSEN (1909) have described the formation of deep-water in the Greenland–Norwegian Sea as taking place to a small extent in the Norwegian Sea but primarily in the Greenland Sea. This latter formation was described as being the source of the deep-water of the Polar Basin also. It is within the cold centre of the Greenland gyral that this formation presumably takes place. However, the deep-water of the Polar Basin was shown by NANSEN (1902), SVERDRUP (1933), SHIRSHOV (1944) and others to be − 0·91° or warmer. This temperature is characteristic of the deep layers of the Norwegion Sea and of the Norwegian Current as it comes from that sea. The entire water column within the core of the Greenland gyral is appreciably colder than this figure, and this cold water is completely cut off from the Polar Basin by the presence of warmer deep-water in the northern part of the Greenland Sea. Therefore it is suggested that it is in the Norwegian Sea not in the Greenland Sea, that the greatest amount of the deep-water of the Polar Basin is formed. The very cold deep-water formed in the Greenland Sea apparently is gradually mixed with the much greater volume of warmer deep-water from further

south which is found around the periphery of the Greenland gyral thus losing its identifying characteristics of very low temperature. As the result of this mixing, some of it may eventually find its way into the Polar Basin and so make a minor contribution to the deep-water of that basin.

Table 3. Three stations located on east the, north and northwest sides respectively of the Greenland gyral where water typical of the Norwegian Sea is found.

Depth (m)	*Temp.* (0°C)	*Salinity* (‰)	*Oxygen* (ml/L)
Station No. 33. 14–15 *March* 1955. 76° 44′ *N.*, 11° 06′ *E.* *Depth* 1920 *m.*			
1	3·22	34·99	7·49
38	3·45	35·06	7·36
77	3·47	35·09	7·14
159	3·22	35·09	6·74
337	3·06	35·09	6·71
534	1·35	34·99	6·34
689	—	34·94	6·68
870	− 0·42	34·93	6·52
1053	− 0·64	34·92	6·59
1242	− 0·79	34·92	6·24
1532	− 0·91	34·92	6·65
1825	− 0·96	34·92	6·75
Station No. 36. 17 *March* 1955. 79° 08′ *N.*, 00° 20′ *E.* *Depth* 2834 *m.*			
1	− 1·59	34·33	8·13
42	− 1·54	34·35	7·95
83	2·42	34·94	7·20
168	2·61	35·02	7·18
344	2·20	35·01	7·18
531	1·51	35·01	7·18
590	—	34·93	—
740	0·08	34·92	7·17
1117	− 0·48	—	7·16
1498	− 0·71	34·93	7·11
1885	− 0·85	34·93	7·11
2119	− 0·87	34·93	7·10
Station No. 37. 17 *March* 1955. 77° 32′ *N.*, 04° 20′ *W.* *Depth* 1829–2926 *m.* (*deepened rapidly during station*)			
1	0·21	34·60	7·16
37	0·20	34·60	7·73
76	0·62	34·66	7·17
154	1·82	34·92	7·16
324	1·67	35·01	6·71
519	0·59	34·97	7·33
581	0·40	34·96	7·37
793	− 0·29	34·93	7·27
1014	− 0·44	34·93	6·90
1402	− 0·67	34·83	7·14
1815	− 0·89	34·92	7·17
2250	− 0·96	34·92	7·16

At one station occupied by the *Nautilus* in the Polar Basin, a single observation of − 0·01° was found at 1648 metres (SVERDRUP, 1933). This observation does not fit in well with the others from the same expedition, but if it is correct, it may represent a surge of Greenland gyral water which was pushed through the warmer water normally lying north of it. Nowhere else in the Polar Basin is deep-water found which

is this cold, and it is not likely that much of it actually breaks through into this basin very frequently.

There is evidence that deep-water formation in the North Atlantic Ocean is not taking place under present climatic conditions (WORTHINGTON, 1954). However, its possible formation in the Norwegian Sea as recently as 1951 has been suggested by METCALF (1955). Although the oxygen data available are not considered sufficiently accurate to shed much light on this subject, 90% oxygen saturation and above in the deep-water of the Greenland–Norwegian Sea is not uncommon indicating a certain amount of recent communication between the surface and the deep-water. Generally, the oxygen saturation is higher in the core of the Greenland gyral than elsewhere in the region indicating more activity there. It is suggested that deep-water formation, while probably not taking place each winter, does occur periodically during particularly cold winters and more frequently, though not necessarily in greater amounts, in the Greenland gyral than in the Norwegian gyral.

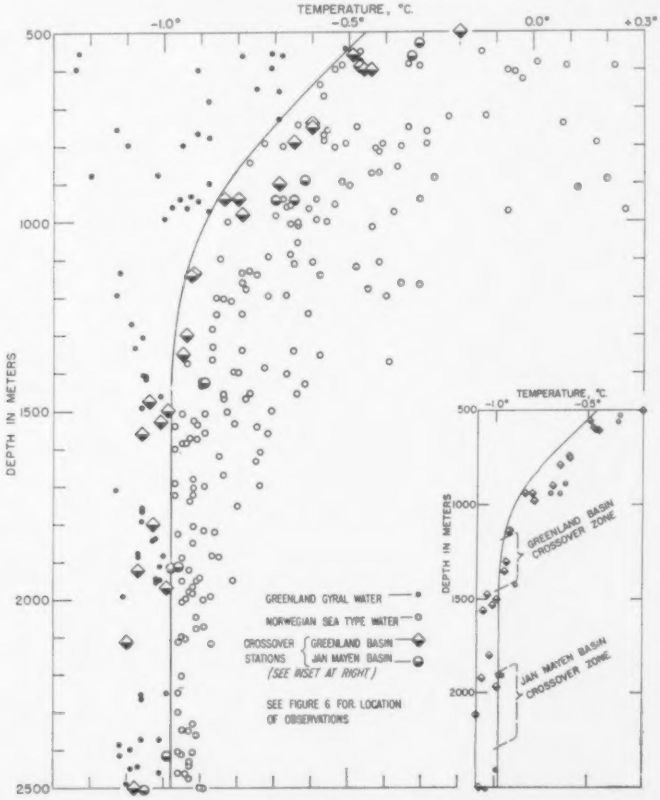

FIG. 5. Temperature vs. depth diagram.

TEMPERATURE–DEPTH RELATIONSHIP

In the intermediate water (600 to 1500 metres) and the deep-water, there is little if any distinct salinity variation geographically in the area studied. A temperature-salinity diagram showed a separation into two groups on the basis of temperature

alone, the salinity in the deep-water being 34·92 – 34·93‰ with remarkably little spread throughout the entire Greenland–Norwegian Sea. For this reason, a temperature vs. depth diagram has been drawn using all observations between 500 and 2500 metres from those stations extending deeper than 1500 metres (FIG. 5).

Observations from stations in the centre of the Greenland Sea and from stations in the centre of the Norwegian Sea were plotted, and it was found that a smooth curve could be constructed separating the two groups. Below about 1450 metres, this curve becomes a straight line at – 0·98°. The water of the core of the Greenland gyral lies on the cold side of the curve throughout its length. However, observations falling on the warm side of the curve were found not only throughout the Norwegian Sea but also around the periphery of the Greenland gyral on the east, north and northwest sides, as would be expected from the earlier discussion of the circulation (FIG. 6).

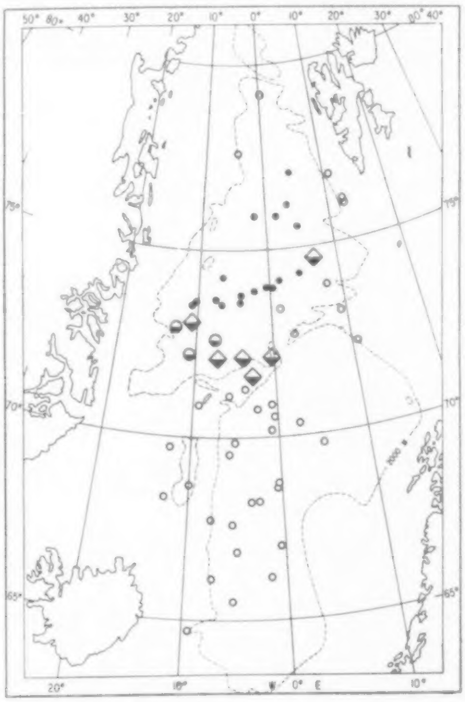

FIG. 6. Location of stations used in construction of FIG. 5.

Not all the stations occupied throughout the region fall readily on one side or the other of the curve throughout its length. Out of the 62 stations represented in FIGS. 5 and 6, nine showed a cross-over from the warmside of the curve in the upper levels to the cold side in the deeper levels, indicating that they represent conditions intermediate between the two main classes. All of these ‘ cross-over ’ stations, as they have been termed, are found along the southwest, south and southeast margins of the Greenland Sea. They all show water in the upper levels with Norwegian Sea characteristics and water in the deeper levels with Greenland gyral characteristics.

In eight of the nine cases, a well defined submarine ridge lies a short distance upstream of the stations which suggests that the height of the ridge may determine the depth in the water column at which the cross-over takes place by affecting the flow of the deep-water.

Table 4. A station exhibiting Norwegian Sea intermediate water lying over Greenland gyral deep water.

Station No. 43. 19 *February* 1954. 72° 05′ *N.*, 04° 00′ *W. Depth* 2441 *m.*

Depth (m)	*Temp.* (°C)	*Salinity* (‰)	*Oxygen* (ml/L)
1	− 1·70	34·50	8·63
20	− 1·61	34·54	—
40	− 1·66	34·53	8·65
60	− 0·98	34·62	—
80	0·87	—	7·57
100	1·36	34·96	—
123	1·41	34·96	7·01
148	1·37	34·96	—
173	1·22	34·99	7·44
197	1·10	34·98	—
247	0·95	34·97	7·28
296	0·64	34·99	—
323	0·48	—	7·21
371	0·29	34·95	7·27
749	− 0·60	34·97	7·17
1134	− 0·92	34·92	6·37
cross-over 1526	− 1·01	34·98	6·98
(see text) 2114	− 1·10	34·97	6·78

Table 5. A Jan Mayen Basin station exhibiting a cross-over within the deep water from Norwegian Sea type to Greenland gyral type.

Station No. 42. 19 *February*, 1954. 72° 32′*N*, 07° 34′W. *Depth* 2743 *m.*

Depth (m)	*Temp.* (°C)	*Salinity* (‰)	*Oxygen* (ml/L)
1	− 1·73	34·73	8·10
20	− 1·76	34·69	8·33
51	− 1·76	34·70	8·35
101	− 0·17	34·83	8·26
152	0·99	34·98	8·39
202	—	35·01	8·51
372	0·19	34·97	8·14
563	− 0·33	34·96	7·91
941	− 0·70	34·94	7·94
1424	—	34·95	7·91
1912	− 0·96	34·95	7·37
cross-over 2509 (see text)	− 1·05	34·92	7·06

Those five stations (FIG. 6) which lie along the south and southeast margins of the Greenland Sea just downstream from the East Jan Mayen Ridge, show cross-overs in the intermediate water between 1200 and 1450 metres (FIG. 5 inset; Table 4). This is approximately the depth of the East Jan Mayen Ridge as shown by STOCKS (1950).

The three stations (Table 5) in the Jan Meyan Basin exhibit cross-overs in the deep water between 1900 and 2300 metres (FIG. 5 inset). The sill depth of the North Jan Mayen Ridge upstream from these stations is very imperfectly known, but the figures 1900 to 2300 are not unreasonable. The Jan Mayen Basin is open at the east end to the Greenland Basin at great depth and is filled below the depth of the cross-over with typical Greenland gyral deep-water.

The remaining cross-over station, lying north of the Jan Mayen Basin, shows a cross-over at 1450 metres. Paucity of topographical data makes the relationship, if any, between the bottom topography and the cross-over depth impossible to determine. When further survey work is carried out in this area, it will be interesting to discover whether there is a submarine ridge or mount upstream from this position. A better knowledge of the bathymetry and more oceanographic field data than are now available is required before this can be resolved. Accurate navigational data is especially important in this type of oceanographic problem. Unfortunately it is also especially difficult in this region.

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Woods Hole Oceanographic Institution Contribution No. 1101.

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Total and organic phosphorus in waters of the Bering Sea, Aleutian Trench and Gulf of Alaska*

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Abstract—Total phosphorus was determined on some 170 samples from eleven stations in the Bering Sea, the Aleutian Trench, and the Gulf of Alaska. Samples ranged in depth from the surface to 7000 m. In these samples organic phosphorus, estimated as the difference between total and inorganic phosphorus, bears an inverse relationship to the distribution of inorganic phosphorus. Surface waters, generally low in inorganic phosphorus, contain up to 1·0 μg. at./L organic phosphorus, with a grand average of 0·27 μg. at./L for the upper 200 m. The amount of organic phosphorus present in surface waters reaches values as high as 47 per cent of the total. On the other hand, waters below about 200 m. have little or no measurable amounts of organic phosphorus. In its vertical distribution, total phosphorus varies at the most by a factor of three and is more or less uniform with depth compared to the inorganic phosphorus. Inferences are drawn concerning the nature of organic matter and the state of organic phosphorus in deep waters. The observed distribution of various forms of phosphorus substantiates the theory that the major part of the phosphorus cycle is enacted in the surface layers.

INTRODUCTION

PHOSPHORUS is present in sea water in solution and particulate solid state and in both inorganic and organic compounds. Knowledge is limited concerning the quantitative distribution of phosphorus among its various forms in sea water, as well as concerning the nature of the compounds in which it is organically bound. Such information is of interest in connection with the biogeochemical processes involving transfer, accumulation, and partition of phosphorus in the marine environment and in connection with problems of organic production in the sea. The significance of organic phosphorus determinations in oceanographic studies has been discussed by KETCHUM, CORWIN and KEEN (1955) who reported on the results of analysis of nearly 1000 samples from the equatorial Atlantic Ocean. These authors also showed that in waters below 1000 m, phosphorus was essentially present in the inorganic form, while surface waters contained an important fraction of the element in organic form.

Voluminous data on the distribution of inorganic phosphorus in Pacific waters are available but only a few analyses on organic phosphorus have been reported and these are primarily from coastal environments. HANSEN and ROBINSON (1953) found 0·36–0·59 μg atom/L of organically-bound phosphorus in Dabob Bay in Puget Sound. More recently TAKEDA (1957) studied the relationship between organic phosphorus and plankton in Pacific surface waters off the eastern shore of northern Honshu. He found inorganic phosphorus uniformly distributed in surface waters during May when the plankton was propagating, while total phosphorus varied with

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the propagation of plankton. . Total phosphorus decreased with increase of the standing crop of phytoplankton and vice versa. He gave no estimate, however, of organic phosphorus in the waters investigated. ROCHFORD (1958) studied the degree of the conservative character of total phosphorus as a means of identifying East Australian water masses and reported on the particulate phosphorus content of coastal waters.

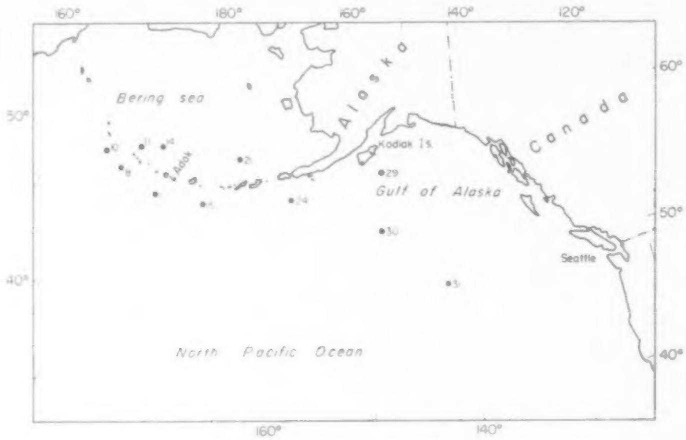

FIG. 1. Location of stations.

The present study was conducted in the summer of 1957 during *Brown Bear* Cruise 176, as part of the International Geophysical Year programme of the University of Washington. Water samples were collected from eleven stations in the Bering Sea, Aleutian waters and the Gulf of Alaska to investigate the vertical distribution of total, inorganic, and organic phosphorus (FIG. 1). Particular emphasis was placed on deep and bottom waters for which organic phosphorus data are virtually non-existent.

ANALYTICAL PROCEDURE

KETCHUM, CORWIN and KEEN (1955) investigated the accuracy and precision of HARVEY's autoclave digestion method (HARVEY, 1948) for measuring total phosphorus in sea water, and recommended its use in preference to the routine analysis of soluble inorganic phosphorus. Because of the lack of a suitable autoclave this procedure was not used during the present study and the organic matter was digested with perchloric acid, following the procedure described by HANSEN and ROBINSON (1953).

Heavy polyethylene bottles (16-oz.) with buttress caps were used for storage of samples (500 c.c.). The bottles were cleaned by scrubbing the walls with a rubber policeman and warm 10% hydrochloric acid, then rinsing several times with tap water, distilled water and finally the sea water to be analyzed. Prior to analysis, organic matter adhering to the walls was dispersed back into the sample by adding 2 cc. of concentrated hydrochloric acid and scrubbing with a rubber policeman. A 50-cc. aliquot was then transferred with a volumetric pipette into a 125-cc. Vycor Erlenmeyer flask, followed by 3 cc. of 70·7% perchloric acid. The organic matter was oxidized and arsenic removed, as described by HANSEN and ROBINSON (1953). Because of the limited number of Vycor flasks available, only twelve digestions were conducted at once, of which two were reagent blanks. After digestion the residue was dissolved in distilled water and transferred to a 50-cc. volumetric flask and the phosphorus content was measured spectrophotometrically, using the method described by WOOSTER and RAKESTRAW (1951). Although the perchloric acid digestion procedure of HANSEN and

ROBINSON is more laborious and time-consuming than HARVEY's method, it was found to have an accuracy and reproducibility comparable to that of HARVEY's method as reported by KETCHUM, CORWIN and KEEN (1955). Replicate analyses of a standard solution of disodium glycerophosphate (1 and 2 μg. at./L) gave recoveries within 5 per cent of the original amount taken and the reproducibility determined from eleven calibrations run during the period of analysis was 7 per cent.

Inorganic phosphorus was determined aboard ship immediately after sampling, using a Beckman model DU spectrophotometer and the procedure described by WOOSTER and RAKESTRAW (1951). Total phosphorus content of the samples was measured in the shore laboratory and the organic fraction was estimated by finding the difference between the total and inorganic phosphorus. Only those differences exceeding 7 per cent of the total were considered significant and are reported in this paper as the organic phosphorus content.

In the analysis of total phosphorus, arsenic interference is eliminated by its removal as the trichloride. On the other hand, inorganic phosphorus determination includes the arsenate content of sea water. This may result in erroneously low values for the estimated organic phosphorus; however, the low arsenate content of sea water (GORGY, RAKESTRAW and FOX 1948, give 0·03 to 0·70 μg. at./L) and the relatively high concentration of inorganic phosphorus in the waters investigated make this error insignificant.

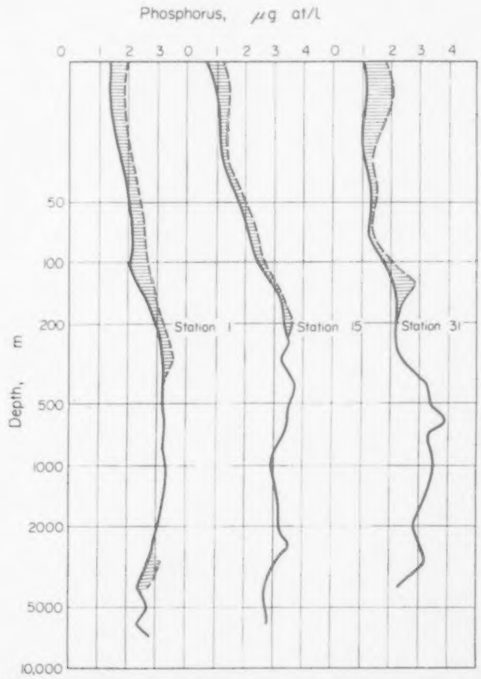

FIG. 2. Vertical distribution of total, inorganic and inorganic phosphorus at Stations 1, 15 and 31. Broken line = total phosphorous. Solid line = inorganic phosphorus. Shaded area = organic phosphorus.

RESULTS AND DISCUSSION

Tables 1 and 2 show the result of analyses for total and organic phosphorus, respectively, and FIG. 2 illustrates the vertical distribution of total, inorganic, and organic phosphorus at three stations. The data indicate that total phosphorus has a vertical distribution parallel to that of the inorganic form, being lower at the surface than at greater depth. In the eleven stations investigated, surface water contained up to 1·0 μg at./L of organic phosphorus with a grand average of 0·27 μg at./L for the

Table 1. *Total phophorus*, μg. at./1

Sta. No. *Lat.* *Long.*	1 50° 22′N 177° 40′W	8 50° 55′N 177° 23′E	10 51° 08′N 174° 41′E	11 51° 41′N 178° 10′E	14 53° 33′N 179° 35′W	15 51° 02′N 171° 45′W	21 55° 00′N 169° 40′W	24 53° 12′N 162° 27′W	29 56° 24′N 151° 16′W	30 51° 53′N 150° 42′W	31 48° 03′N 142° 50′W
Depth (m)											
0	1·96	1·89	1·49	1·54	2·66	1·28	1·90	—	1·79	2·45	1·83
10	1·83	2·05	1·72	1·96	1·95	1·40	1·74	—	1·50	1·70	2·08
30	2·10	1·64	2·26	2·27	2·03	1·38	2·49	—	1·40	1·85	1·35
75	2·55	3·04	2·72	2·63	2·50	2·43	2·39	—	2·90	2·75	1·23
125	2·93	2·96	3·31	2·66	3·27	3·02	3·00	—	2·42	3·37	2·82
200	3·19	—	3·46	3·03	2·70	3·60	2·80	—	2·65	3·00	2·18
300	3·56	3·51	3·13	3·59	2·80	3·21	2·90	—	2·74	3·40	2·39
500	3·14	3·20	3·12	3·50	3·00	3·33	3·02	—	2·60	3·62	—
700	3·25	2·55	—	3·42	3·10	3·30	3·40	—	3·20	3·56	—
800	3·16	3·40	2·83	3·11	3·34	2·80	3·00	—	3·10	3·32	3·34
1000	3·33	—	3·18	3·11	3·34	2·82	3·00	—	—	3·52	3·46
1500	3·24	3·20	3·30	—	—	—	3·20	—	3·00	3·70	3·16
2000	3·05	3·50	3·46	3·27	—	3·10	3·69	—	2·70	3·00	2·82
2500	2·86	3·03	—	—	—	3·00	2·96	3·00	—	3·20	3·00
3000	3·14	3·21	3·20	3·14	—	3·00	—	—	—	2·70	3·12
3500	2·98	3·30	3·03	3·02	—	2·86	—	3·10	—	3·00	3·00
4000	2·71	—	2·85	—	—	2·70	—	—	—	—	2·20
4500	—	2·84	2·81	—	—	2·76	—	—	—	—	—
5000	2·71	2·83	2·81	—	—	2·70	—	2·90	—	—	—
5500	2·68	2·63	2·71	—	—	2·68	—	—	—	—	—
6000	2·39	2·57	2·66	—	—	2·70	—	2·85	—	—	—
6500	2·54	2·62	2·65	—	—	2·72	—	2·60	—	—	—
7000	2·74	2·68	2·68	—	—	3·60	—	—	—	—	—

— Sample was not analyzed

Table 2. *Organic phosphorus, μg. at./l**

Sta. No. *Lat.* *Long.*	1 50° 22′N 177° 40′W	8 50° 55′N 177° 23′E	10 51° 08′N 174° 41′E	11 51° 41′N 178° 10′E	14 53° 33′N 179° 35′W	15 51° 02′N 171° 35′W	21 55° 00′N 169° 40′W	24 53° 12′N 162° 27′W	29 56° 24′N 151° 16′W	30 51° 53′N 150° 42′W	31 48° 03′N 142° 50′W
Depth (m)											
0	0·60	0·20	0·20		1·00	0·61	0·50	—	0·32	1·00	0·83
10	0·50	0·24	0·32	0·42	0·25	0·34	0·27	—	0·28		0·96
30	0·40		0·30	0·30	0·30	0·30	0·32	—		0·30	0·30
75	0·34	0·26	0·25	0·34	0·24	0·25		—	0·40	0·46	
125	0·50	0·35	0·40		0·49	0·00	0·40	—		0·40	0·28
200		—				0·28		—	0·29		
300	0·40	0·27		0·40				—	0·30		
500								—			—
700			—					—			—
800			0·50					—			
1000		—						—	—		
1500				—	—	—		—			
2000		0·40			—			—			
2500			—	—	—		0·34		—		
3000	0·32	0·34			—		—	—	—		
3500	0·34	0·51			—		—		—		
4000	0·30	—		—	—		—	—	—	—	
4500	—			—	—		—	—	—	—	—
5000				—	—		—		—	—	—
5500				—	—		—	—	—	—	—
6000				—	—		—		—	—	—
6500				—	—		—		—	—	—
7000		—		—	—		—	—	—	—	—

*For samples with organic phosphorus greater than 7% of the total.
—Sample was not analysed.
Blank space = sample with insignificant or no organic phosphorus.

upper 200 m. None of the surface samples, however, gave an organic phosphorus concentration higher than the inorganic level as reported in KETCHUM, CORWIN and KEEN (1955). In Table 3 the percentages of total phosphorus present in the organic form in the upper 200 m are given and show that the organic fraction reaches as much as 47 per cent of the total and averages 18 per cent. The waters below about 200 m, however, showed no significant differences between total and inorganic phosphorus concentrations (Table 2) except in a few samples amounting to less than 5 per cent of the total.

The present observed distribution of organic phosphorus resembles the distribution found by KETCHUM, CORWIN and KEEN (1955) in the equatorial Atlantic, where 95 per cent of the surface samples contained significant quantities of organic phosphorus, while deeper waters (in this case below 1000 m) had no measurable amounts.

Table 3. Percentage of total phosphorus in the organic form upper 200 m

Station No.	1	8	10	11	14	15	21	29	30	30
Depth, (m)										
0	30·6	10·6	13·4		37·6	47·0	26·3	17·8	29·0	45·5
10	27·4	11·7	18·6	21·4	12·8	24·2	15·5	18·6		46·0
30	19·0		13·3	13·2	14·8	21·7	12·8		35·0	22·2
75	13·3	8·6	9·2	12·9	9·7	10·3		13·8	16·7	
125	17·0	11·8	12·1		15·0		13·3		11·9	10·0
200		—				7·8		11·0		
Ave.*	21·5	10·7	13·3	15·8	18·0	22·2	17·0	15·3	16·6	30·9

Grand average = 18·1%
*Average for samples with organic phosphorus greater than 7% of the total.

The insignificance (analytically) of organic phosphorus in the deep waters raises the question as to the processes involved in depriving deep waters of measurable concentrations of this fraction of phosphorus. ZOBELL (1946) discussed the regeneration of phosphorus in sea water and referred to a number of earlier investigators who suggested the rapidity with which phosphorus is regenerated from organic matter by bacterial decay. GOLDSCHMIEDT, METTENLEITER and BORCHARDT (1958) identified alkaline phosphatase as one of the principal enzymes in sea water and from serial investigations these authors showed that the concentration of the enzyme increased with the depth of the water and with distance from land. Phosphatases, enzymes which catalyze the breakdown of phosphate-containing substrates, release phosphorus from organic combination and may account for the absence of significant concentrations of organic phosphorus in deep waters. The present investigation substantiates the theory that, at least in oceanic environments with great depths of water, the major part of the phosphorus cycle in the ocean takes place in the euphotic zone.

There are indications that oceanic deep waters contain organic matter, but information on its nature and composition is insufficient to permit predictions as to the state of organically-bound phosphorus. PLUNKETT and RAKESTRAW (1955) measured the dissolved organic carbon in a number of deep-water samples from six stations off the California coast and in the Northwestern Pacific. They found 0·59–2·82 mg/L of dissolved organic carbon in waters deeper than 500 m. GAST and THOMPSON (1958) considered that the difference between observed total and free boron in sea

water was due to the presence of polyhydroxy organic compounds which complex with part of the boron. They estimated that as much as 0·015 millimoles of organic polyhydroxy compounds may be present in water deeper than 500 m in the North-east Pacific. Until the present methods of measuring total and inorganic phosphorus in sea water are materially improved, the presence or absence of organic phosphorus compounds and the concentration or organic phosphorus in deep waters will remain uncertain.

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La 'soucoupe plongeante', engin de prospection biologique sous-marine

J. -M. PERES

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Abstract—The COSTEAU's 'diving saucer' is now ready for diving down to 900ft. The first scientific dive in Ajaccio Bays has given the opportunity of a short account on the vertical distribution of animals and algae, both on rocky and soft bottoms from 15 fathoms down to 100 fathoms deep. The engine seems easy to drive and allows observations on substratum at a very short distance if necessary; its speed is adequate for a quick survey of a large area of bottom where the flora and fauna are well known. The diving saucer seems less adequate for plankton investigations.

SI DEPUIS que les bathyscaphes sont entrés dans une phase d'exploitation scientifique méthodique l'étude directe des grands fonds a fait des progrès considérables, il n'en restait pas moins une zone dans laquelle cette étude directe était très difficile. En effet, d'une part on ne peut exploiter le scaphandre autonome au delà d'une profondeur de 60 m. D'autre part, étant données les difficultés et le coût élevé de la mise en oeuvre d'un bathyscaphe, les plongées ne peuvent être considérées comme 'rentables' qu'aux profondeurs excédant 500 m au moins, et même 1,000 m.

Pour l'espace compris entre 60 et 500 m l'observation directe n'a pu être assurée jusqu'ici que par des engins non-autonomes et notamment par les tourelles Galeazzi qui exigent évidemment d'être manoeuvrées à partir d'un navire d'une certaine importance.

La 'soucoupe plongeante' conçue et réalisée par le Cdt. J. Y. COUSTEAU vient combler cette lacune dans les moyens de prospection autonome.

Le 3 février 1960, de 12h 15 à 16h 00, j'ai éxécuté la première plongeé de caractère scientifique à 182 m de profondeur, sur la rive Nord du Golfe d'Ajaccio au Sud de la Tourelle de Gardiola.

La plongée s'est déroulée comme suit :

(a) Descente directe (à la verticale) de la surface à 70 m.

(b) Descente en suivant le fond de 70 à 182 m.

(c) Remontée de 182 à 30 m en suivant le fond et en épousant tous les accidents de celui-ci.

(d) Remontée à la verticale de 30 m à la surface.

Le point choisi pour la plongée était remarquable par la présence d'un grand nombre de roches parsemant le sédiment et qui paraissaient appartenir à deux catégories : des blocs isolés de quelques mètres cubes au maximum d'une part; d'autre part des massifs ou des dalles rocheuses dressées atteignant 5–6 mètres de haut.

Dans la zone de plongée la pente du fond (les pointements rocheux exceptés bien entendu) était de l'ordre de 15° jusqu'à la rupture de pente située vers 140 m de profondeur; au delà la pente est de l'ordre de 40 à 45°.

Jusque vers 50–55 m : le sédiment est un sable grossier surtout organogène, très peu vaseux; les *ripple marks* y sont présents mais faibles, irréguliers, sinueux. La nature même du sédiment indique qu'il y a un transport assez actif vers la profondeur, concrétisé surtout par d'assez nombreux débris de Posidonies (feuilles et rhizomes). Vers 60 m le sable grossier est très légèrement plus vaseux, mais on observe de grands *ripple marks* profonds de 20 cm environ, avec un espacement entre deux crêtes de l'ordre de 50 cm, et dont l'axe est dans le sens de la ligne de plus grande pente et indique donc un courant suivant les courbes de niveau; les débris de Posidonies se trouvent surtout dans les creux de ces *ripple marks*. Vers 70 m le sédiment devient plus vaseux, les *ripple marks* disparaissent et les débris de Posidonies, encore plus nombreux sont généralement orientés avec leur grand axe dans le sens de la pente.

A partir de 90 m environ la fraction fine augmente fortement, et, dès 100 m, on peut dire qu'on est sur un fond de vase légèrement mêlée de sable fin. Le nombre des débris Posidonies diminue beaucoup dès 90–100 m, puis ceux-ci disparaissent pratiquement à partir de la rupture de pente (140 m environ); il est probable que les débris qui arrivent jusqu'à cette profondeur tombent jusqu'en bas de la pente. Dès 140 m le fond peut être considéré comme de vase argileuse.

PEUPLEMENT BENTHIQUE DES SEDIMENTS

(a) Vers 40–50 m de profondeur le sable organogène grossier est pratiquement dépourvu d'algues; Les Mélobésiées ne paraissent pas exister sur les gros débris coquilliers. On observe en revanche vers 50 m un horizon assez étroit (qu'on pourrait presque qualifier de ceinture) où le gros Echinide Régulier *Sphærechinus granularis* abonde, en peuplements denses pouvant grouper jusqu'à 10–15 individus sur une surface de l'ordre de 1 à 1,5 m 2. Les *Sphærechinus* existent plus haut, mais en exemplaires isolés.

(b) Vers 60 m on observe un peuplement régulier mais clairsemé de *Vidalia volubilis* (1–2 individus par mètre carré) qui paraissent sortir directement du sédiment et sont sans doute fixés sur les plus gros des débris coquilliers; aperçu quelques *Serranus cabrilla*.

(c) Entre 70 et 80 m, le sable grossier, déjà un peu vaseux, est parsemé de tests d'Oursins Irréguliers, surtout *Ova canalifera* et d'un Spatangide violacé qui parait être *Spatangus purpureus*. Le Téléostéen *Serranus cabrilla* est assez commun et on observe de petites troupes de *Anthias anthias*, ainsi que quelques individus de *Gobius lesueuri*. Sur les plus gros des débris coquilliers et sur de petits fragments de concrétionnement (provenant sans doute de massifs rocheux voisins) on observe des Mélobésiées roses mêlées à la petite Chlorophycée *Palmophyllum crassum*. Fichés dans le sable vaseux on relève quelques *Pteroides griseum*. J'ai aperçu également un assez gros bloc de concrétionnement portant trois individus vivants de *Protula* (sans doute *P. tubularia*).

(d) Vers 90 m, profondeur où le sédiment devient nettement plus vaseux, apparaissent assez brusquement les premières *Funiculina quadrangularis* atteignant 40–70 cm de long, toujours disposées obliquement par rapport au fond, et arquées. Les débris portant des Mélobésiées vivantes (avec ou sans *Palmophyllum*) se raréfient. En revanche le fond est parsemé de petits trous

(1 cm de diamètre environ) qui paraissent appartenir au petit Téléostéen *Gobius lesueuri* dont des dizaines d'exemplaires nagent en tous sens, se réfugiant agilement dans les trous dès que la ' soucoupe ' approche. Aperçu également une colonie d'*Alcyonium palmatum*.

(e) Vers 95 m, les Mélobésiées ont totalement disparu; les *Funiculina* et *Gobius lesueuri* sont toujours présents, ainsi que des *Serranus cabrilla*; aperçu également une petite *Trigla* de couleur rouge à pectorales bien bleutées, qui est sans doute *Trigla hirundo*. Les premiers *Stichopus regalis* apparaissent, mais sont encore de petite taille. Vu également une *Pennatula rubra*.

(f) Entre 105 et 115 m, les éléments principaux du peuplement sont toujours les mêmes : *Funiculina quadrangularis*, *Stichopus regalis* (plus abondante et représentée par des individus plus grands), *Gobius lesueuri* (commun), *Serranus cabrilla*, *Trigla hirundo*. Il s'y ajoute une *Holothuria* dont le tégument est plus ou moins couvert de débris et deux nouveaux Octocoralliaires : *Virgularia mirabilis* et *Kophobelemnon* (? *stelliferum*). Aperçu également un *Protula tubularia*, et un exemplaire de *Callionymus* qui est sans doute *C. maculatus*, espèce assez commune dans l'étage circalittoral.

(g) De 120 à 135 m, le peuplement reste pratiquement identique : les deux Holothurides et le *Gobius* sont toujours communs, et *Trigla hirundo* parait un peu plus abondant qu'il ne l'était plus haut; aperçu également un grand specimen d'*Alcyonium palmatum* (environ 25 cm de haut), un *Pteroides griseus* et un gros *Microcosmus sulcatus*. Vers 120–130 m j'ai vu aussi deux exemplaires d'un Céphalopode Octopode qui m'a paru être une *Eledone* et des terriers à orifice circulaire de 10–12 cm de diamètre qui sont sans doute imputables à cette espèce, mais autour desquels les débris ne sont pas très nombreux (moins me semble-t-il qu'au voisinage d'un terrier classique d'*Octopus*).

(h) A partir de 140 m environ, c'est-à-dire à la rupture de pente, le tableau du peuplement change assez nettement. Le *Stichopus*, l'*Holothuria* et le *Gobius* disparaissent (ainsi que les petits trous du fond); les *Funiculina* deviennent plus petites et plus rares, mais en revanche le nombre de *Virgularia mirabilis* augmente ainsi que celui des *Kophobelemnon*, lesquels sont également plus gros que vers 115 m où j'avais aperçu les premiers. *Trigla hirundo* et *Serranus cabrilla* (dont les exemplaires les plus profonds sont les plus gros) se raréfient entre 140 et 150 m et je n'en ai plus recontré au delà de de cette profondeur, tandis qu apparaissent d'autres Téléostéens : un Triglidé de couleur pâle d'environ 30 cm de long et à corps épais, qui est sans doute *Trigla lyra* (150 m), *Capros aper* (nageant par paires à 20–30 cm au dessus du fond) (160 m), *Cepola rubescens* (se tenant en équilibre, ' debout ' sur sa queue qui ondule vivement) (170 m).

Vers 140 m également apparait l'Eponge globuleuse blanche pédonculée *Rhizaxinella pyrifera*, et, sans aucun doute en raison du fait que le sédiment est une vase argileuse grisâtre, le Crabe ' vasicole ' *Goneplax angulata*, dont je n'ai vu qu'un exemplaire mais qui est sans doute assez commun. En effet l'unique specimen que j'ai vu a disparu dans un terrier ' en puit ' de 3–4 cm de diamétre, et les orifices analogues étaient assez nombreux sur le fond.

Planche I.

Planche II.

Planches I et II. La ' soupcoupe plongeante ' J. Y. Cousteau prête à plonger et en action.

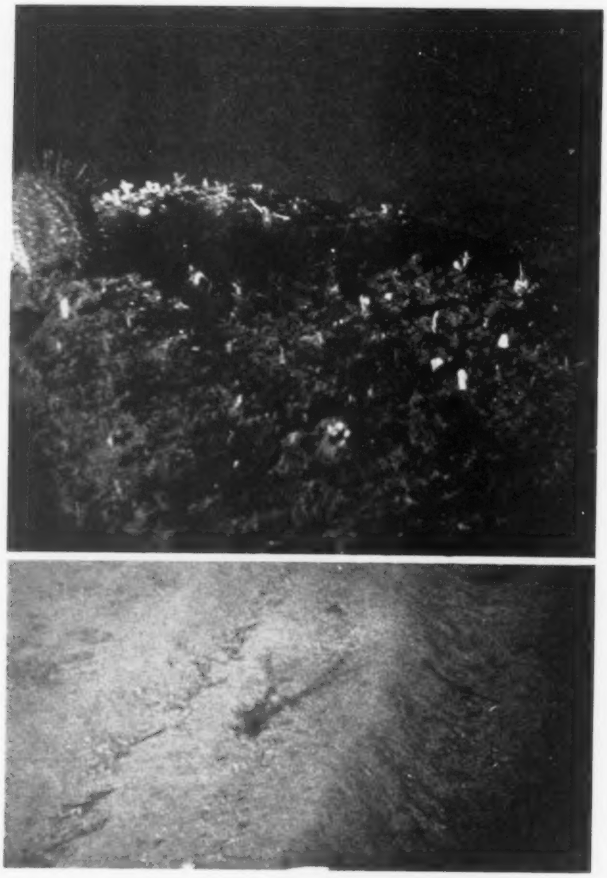

PLANCHE III. Eh haute : crête de rocher à 98 m environ avec Melobésiées diverses, *Palmophyllum crassum*, l'Eponge *Acanthella acuta* (?)
En bas : Fond de sable très légèrement vaseux entre 60 et 70 m avec grands ripple-marks et débris de Posidonies.

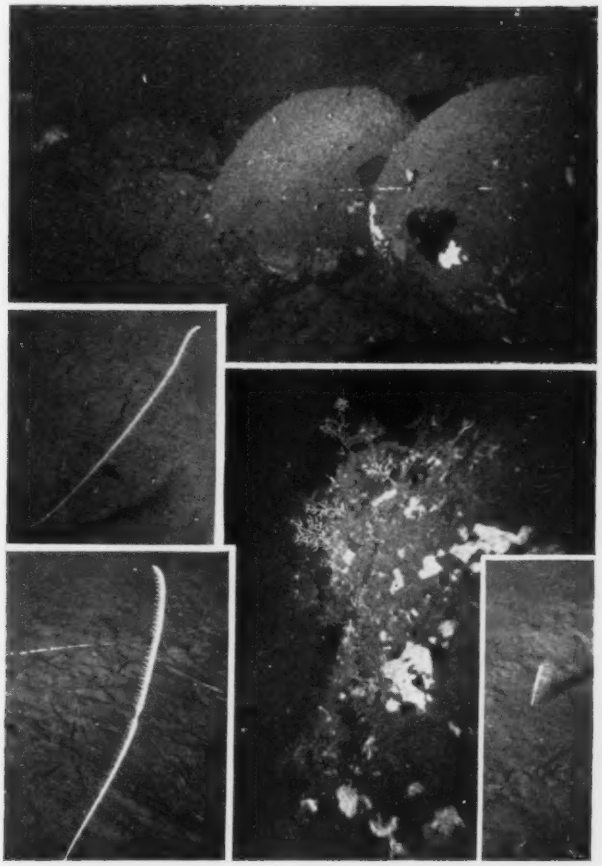

Planche IV. En haut : Blocs rocheux arrondis à surface envasée portant quelques Eponges (*Acanthella acuta*, *Verongia*, et deux espèces encroûtantes). Le peuplement est moins pauvre en surplomb (80–90 m).
A gauche, au milieu et en bas : *Funiculina quadrangularis* (90–140 m).
Au milieu et en bas : paroi rocheuse vers 90 m de profondeur avec abondance d'une Eponge encroûtante blanchâtre et, sur les saillants de la roche, de la Gorgone *Eunicella cavolini* portant de nombreux individus d'*Antedon mediterranea*.
En bas à droite *Kophobelemnon* (à partir de 115 m).

Je n'ai pas poursuivi la plongée au delà de 182 m préférant donner plus de soin aux observations; mais d'après le Cdt COUSTEAU qui était descendu la veille jusqu'à 305 m dans la même zone le peuplement établi à partir de 140 m reste le même jusqu'à cette profondeur, ce qui est d'ailleurs normal.

PEUPLEMENT BENTHIQUE DES SUBSTRATS ROCHEUX

Si j'ai étudié les substrats meubles dans le sens des profondeurs croissantes, j'étudierai au contraire les substrats rocheux en remontant vers la surface, suivant d'ailleurs en cela le programme général de la plongée tel que je me l'étais fixé.

Je vais préciser d'abord que malheureusement je n'ai observé aucun pointement rocheux au delà de la rupture de pente. Tous les rochers étudiée sont entre 110 m et 40 m environ, donc dans l'étage circalittoral.

(a) A 110 m (remontée) Rocher légèrement envasé à peuplement coralligène clairsemé. Une petite Gorgone pâle (peut être du groupe de *Muricæa placomus*), les Eponges sont peu variées et je n'ai reconnu que *Petrosia ficiformis*, *Terpios fugax*, et une *Axinella*, quelques gros *Serpulidæ* (*Protula* ou *Apomatus*), des *Retepora*, de nombreuses *Terebratula vitrea*. Les Ascidies sont représentées par *Rhopalæa neapolitana* (assez commune) et quelques *Microcosmus sulcatus*, mais je n'ai pas observé d'Algues.

(b) A 105 m (descente), un bloc prismatique paraissant couvert d'un mince vernis de vase. Apparemment le taux de couverture sessile est de l'ordre de 50 à 60%, mais il est possible que la pellicule vaseuse qui tapisse la roche entre les animaux renferme (ou protège) une microfaune qui nous est inconnue. Les premières Mélobésiées apparaissent mais seulement sur la face du rocher exposée au Sud. Les Spongiaires sont en majorité, représentés notamment par une *Acanthella* (? *acuta*) une Halichondrine en plaque orangée, *Reniera rosea*, *Chalina*, *Ciocalypta*, *Spirastrella* (? *purpurea*), *Aplysilla sulfurea*. On relève également une *Sabella*, un grand Serpulide (*Protula* ou *Apomatus*), les Bryozoaires *Retepora* et *Porella cervicornis*. un Hydroïde de la famille des *Sertulariidæ*, l'Ascidie *Rhopalæa neapolitana* (plusieurs exemplaires). Le Brachiopode *Terebratula vitrea* est commun (2–3 individus par mètre carré) et j'ai aperçu également un *Inachus* à l'affût, absolument immobile, et, sur le sommet du bloc, une *Holothuria forskali*.

(c) Vers 100–105 m (remontée) la soucoupe franchit un énorme massif rocheux qui parait constitué de deux types différents de substratum; d'une part des rochers irréguliers et anfractueux couverts de concrétionnement et à peuplement assez riche; d'autre part des dalles lisses, subverticales à peuplement apparemment très pauvre. Sur ces dernières il n'y a pratiquement que quelques rares Eponges dont la plus commune parait être *Verongia aerophoba* qui dresse de-ci de-là ses petites cheminées coniques jaune d'or.

Sur les roches où s'est développé le concrétionnement le peuplement est beaucoup plus riche. Les Eponges encroûtantes (indéterminables) sont encore assez nombreuses ainsi que *Acanthella* (? *acuta*) mais la fraction végétale n'est plus néligeable. Les Mélobésiées, d'un rose violacé, couvrent une surface appréciable (peut-être 10–15 pour cent de la surface totale) et sont associées à la Chlorophycée *Palmophyllum crassum*. Je n'ai pas vu de

Terebratula vitrea mais, en revanche j'ai observé quelques rares colonies de *Corallium rubrum*, et un petit rameau de *Dendrophyllia cornigera* ne portant que 4–5 polypes. Il y a des *Retepora*, de nombreuses trompes de *Bonellia* (de grande taille) sortent des anfractuosités; surtout il y a abondance de Gorgonaires, principalement *Eunicella cavolini*, avec quelques colonies éparses de *Muricæ chameleon*. Sur la crête du rocher, à une profondeur qui doit être de l'ordre de 98 m, il y avait plusieurs très gros spécimens de *Echinus melo*.

(d) 88–90 m L'étude des substrats durs de ce niveau comporte deux observations :

(i) 80 m. (descente). Gros blocs arrondis à surface légèrement envasée et à peuplement assez pauvre; quelques Hydroïdes (du groupe *Halecium*), un specimen de l'Eponge *Tuberella aaptos*, une *Bonellia*, quelques *Terebratula vitrea* et *Rhopalœa neaploitana*.

(ii) Vers 85–90 m (remontée) la ' soucoupe ' a franchi un ensemble de dalles, inclinées à 70° environ sur l'horizontale, et d'aspect assez lisse. Le peuplement y est assez pauvre, sauf au voisinage immédiate du sommet, et représenté par quelques rares Eponges (quelques *Acanthella* et surtout une forme encroûtante blanchâtre) et par quelques très grosses *Holothuria* noires (atteignant 25–30 cm); j'y ai aperçu dans une fissure un grand *Labrus merula* (?). Au voisinage du sommet, situé vers 85 m environ le peuplement est nettement plus riche : aux Mélobésiées et aux *Palmophyllum crassum* se mêlent les premières *Peyssonnelia* non calcifiées, tandis que *Eunicella cavolini* se raréfie; j'y ai aperçu également une petite colonie de *Corallium rubrum* et un rameau mort de *Dendrophyllia cornigera*; l'Eponge encroûtante blanchâtre se réfugie, vers le sommet de la dalle, dans les fissures où elle accompagne *Petrosia ficiformis*.

(e) Roche subverticale assez irrégulière (remontée) étudiée de 67 à 60 m. L'intérêt de ce bloc est que son sommet porte la biocœnose précoralligène avec large dominance (80% de la surface) de *Halimeda tuna*, qui supplante les *Peyssonnelia* non calcifiées. Lorsqu'on fait l'ascension de la roche sur sa face sud on note successivement de bas en haut : l'apparition des *Udotea petiolata* qui paraissent rester éparses – l'extension en grandes plaques de l'espèce calcifiée *Peyssonnelia polymorpha* qui plus bas n'existait qu'en petites taches. – l'apparition des *Halimeda*. Sur les ressauts de la région moyenne du bloc il y a encore des *Eunicella cavolini* (avec même quelques rares *Muricæa chameleon*); la distribution des *Eunicella cavolini* mériterait une étude approfondie, mais, à première vue il semble que la lumière ne soit pas le seul facteur, et que la vitesse plus ou moins grande du courant dominant (certainement très variable d'un point à un autre en fonction de la microtopographie) joue un rôle non négligeable. Sur les replats rocheux et sur le sommet se trouvaient plusieurs gros specimens de *Scorpæna scrofa*. Dans les fissures j'ai relevé d'assez nombreuses Rhodophycées, encore quelques spécimens d'*Acanthella*, une Eponge rose en grandes plaques qui pourrait être voisine des *Hymedesmia*, et quelques exemplaires d'un Madréporaire jaune d'or qui est peut-être *Leptopsammia pruvoti*.

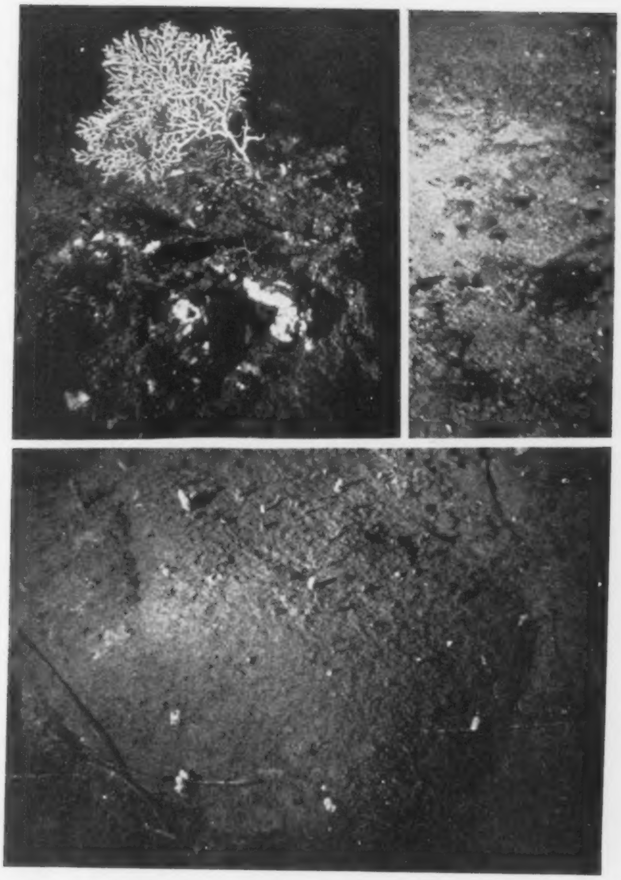

Planche VI. En haut à gauche : Sommet d'un rocher à peuplement coralligène concrétionné. La grande Gorgone est une *Muricea* et porte de nombreuses Ophiurides (sans doute *Ophiacantha setosa*); la petite Gorgone qui apparait en dessous de la *Muricea* est *Eunicella cavolini*. (vers 100 m de profondeur).

En haut à droite : bloc de *Protula tubularia* avec trois individus épanouis, sur fond de sable grossier un peu vaseux (70-80 m).

En bas : gros bloc rocheux de forme arrondie à surface légèrement envasée, portant les Eponges *Acanthella acuta* et *Verongia aerophoba* et quelques *Terebratula vitrea* (80 m environ).

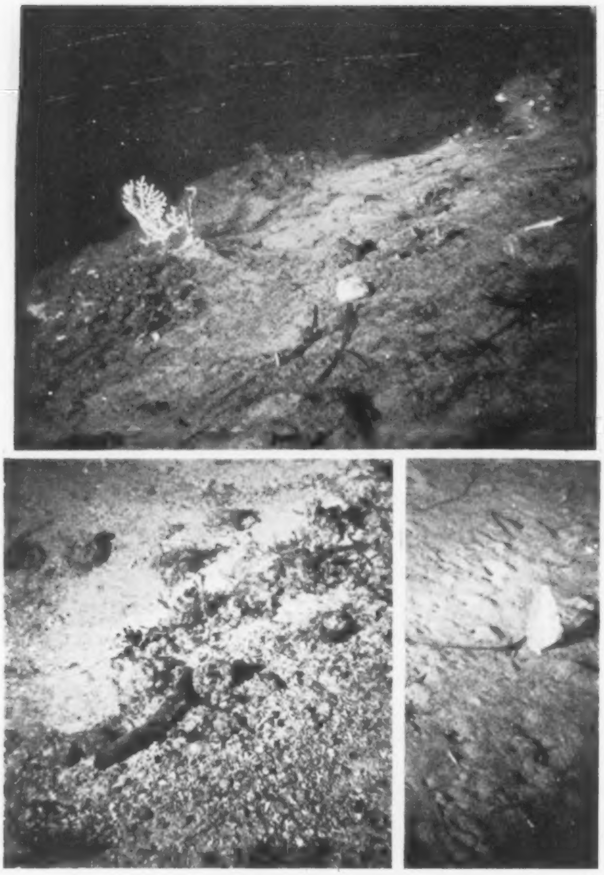

PLANCHE V. En haut : Aspect de la pente vers 70–80 m avec blocs isolés de concrétionnement dont l'un porte un individu de *Muricea chameleon*. Sur le sable vaseux on voit : vers le milieu du cliché un test de l'Echinide *Ova canalifera*; vers la droite un *Pteroides griseus* et un *Callionymus maculatus*; un peu partout débris morts de Posidonies.

En bas à gauche : Fond de sable grossier et gravier coquillier avec l'algue *Vidalia volubilis*, des Algues calcaires, et *Holothuria* (probablement *H. tubulosa*). (60 m).

En bas à droite, *Pennatula* (sans doute *P. rubra*) sur vase sableuse parsemée de trous de *Gobius lesueuri* (95–100 m).

(f) Vers 35 m de profondeur sur les pans rocheux verticaux exposés au Sud commencent les peuplements algaux photophiles de l'étage infralittoral, les fissures présentant encore en enclaves, suivant leur profondeur ou leur orientation, soit la biocœnose coralligène, soit la biocœnose précoralligène. Les *Chromis* nagent en blancs serrés dès 40 m de profondeur, et succèdent donc vers le haut aux *Anthias*

CONCLUSIONS ET CONSIDERATIONS SOMMAIRES SUR L'UTILISATION DE LA SOUCOUPE PLONGEANTE POUR LA PROSPECTION SOUS-MARINE

Du point de vue particulier de la plongée que j'ai effectuée on ne peut évidemment guère tirer de conclusions, du fait même qu'il s'agit d'une plongée unique portant sur des peuplements benthiques dont la distribution verticale générale est assez bien connue. L'observation de certaines espèces dans leur milieu apporte cependant des détails nouveaux : le fait que *Goneplax angulata* possède un terrier; le fait que *Gobius lesueuri* qui possède également un terrier est extraordinairement commun, alors qu'il n'est jamais récolté en très grand nombre par les engins traînants, rant à cause de sa petite taille qu'en raison de son agilité. En ce qui concerne la biocœnose coralligène, il est confirmé qu'elle peut exister au même niveau que les fonds meubles les plus profonds de la marge continentale, donc sur toute l'extension verticale de l'étage circalittoral; est confirmée aussi à vue, la séparation nette du coralligène et du précoralligène en deux biocœnoses distinctes, séparation suggérée par J. LABOREL (1960) dans un récent travail. La question du taux de couverture du substrat par les biocœnoses appellerait encore des recherches; ce taux est sûrement de 100 pour cent pour le précoralligène; pour le coralligène la couverture à 100 pour cent ne parait pas obligatoire, ou en tous cas, sur certains substrats, il n'y a qu'une fraction de l'épifaune qui est vivante. L'appauvrissement qualitatif et quantitatif de la biocœnose coralligène quand la profondeur croît est très net.

D'un point de vue général la ' soucoupe plongeante ' paraît devoir être un engin utile et rentable. Le modèle en service est conçu pour une profondeur de 300 m, mais un autre est en construction pour atteindre 1000 m. Lorsqu'il sera réalisé in n'y aura plus aucune raison d'utiliser un bathyscaphe pour l'étude des fonds n'excédant pas 1000 m.

Il ne m'appartient pas de traiter du point de vue technique et je me placerai ici du strict point de vue de l'utilisateur. La soucoupe plongeante me parait présenter les deux avantages suivants :

1. Mobilité et facilité de manoeuvre. La vitesse lente (de l'ordre de un noeud) est exactement celle qui convient pour faire l'inventaire d'un peuplement assez bien connu au fur et à mesure qu'on le parcourt. La propulsion par réaction à partir de tuyères antérieures donne une grande souplesse de manoeuvre : il est possible, par exemple, d'examiner successivement les diverses faces d'une roche aussi en détail qu'en scaphandre autonome.

2. Examen rapproché. Lorsque l'engin est posé, si un détail exige un examen plus approfondi, l'envoi sur l'avant du lest mobile de 75 Kgs de Mercure fait basculer la ' soucoupe ' et amène le hublot à 25 cm du fond environ.

D'autre part il est évident que la mise en oeuvre est beaucoup plus simple et plus rapide que celle d'un bathyscaphe et que le temps de remorquage est supprimé. En revanche la descente et la montée en pleine eau, relativement rapides, paraissent se

prêter mal aux observations sur le domaine pélagique; encore faudrait-il revoir ce point à l'ocassion d'une plongée plus profonde.

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SHORTER COMMUNICATION

Tertiary sediments from the floor of the Indian Ocean

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UNTIL last year, the only known occurrence of Tertiary strata on the floor of the Indian Ocean was an Eocene to Oligocene basaltic agglomerate dredged from 744 fathoms (1362 metres) on the west side of Providence Reef in 9° 25·8′ S, 50° 56·8′ E by H.M.S. *Sealark* in 1905 (GARDINER, 1907, p. 147). WISEMAN (1936) has described the chemistry, petrology and paleoentology of some of the rocks from this dredge haul, and suggested that part of the foundation of Providence Reef originated through a basaltic eruption of Eocene to Oligocene age. The rock composed of fragmental basaltic material set in a matrix of calcite (British Museum registered No. 1959, 440a (31)) was apparently the first to give direct evidence about the nature of the reef foundations. In this connection it is interesting to recall that drilling on Eniwetok Atoll in the Pacific Ocean revealed basalt at a depth of 692 fms (1266 m) below an Eocene limestone (LADD *et al.*, 1953).

In twelve sediment cores collected from the floor of the tropical Indian Ocean, RIEDEL (1951) found no evidence from the Radiolaria of outcropping Tertiary sediment. Last year, however, Tertiary microfossils were found in two samples collected at or near the sediment surface by early expeditions in the Indian Ocean. These samples are : (1) sounding No. 10 of H.M.S. *Egeria*, collected 22 October 1887, from a depth of 2582 fms (4722 m) at 20° 40′ S, 85° 29′ E, and (2) a sample collected by S.M.S. *Planet* from a depth of 2310 fms (4220 m) at 8° 45′ S, 64° 52′ E.

Egeria sounding No. 10 (British Museum registered No. M3781), originally described as a red clay (Anon., 1888), is one of a series of samples discussed by Sir JOHN MURRAY (1889, 1910) in connection with the dissolution of calcium carbonate in the deeper parts of the ocean. MURRAY indicated on his charts that this sample is a red clay, but a recent analysis (J.D.H.W.) of the material preserved in the British Museum (Natural History) revealed that the carbonate content is about 74 per cent. It is likely that the original material had a higher carbonate content, because the majority of the Foraminifera have apparently been removed from this sample. Although the exact carbonate content of the original material cannot be given, it is clear that it was a highly calcareous ooze and not a red clay. In the Murray Library (section 2, box 12, enclosure 136) there is a manuscript note (author unknown) giving a list of the Foraminifera in *Egeria* sounding No. 10 (*Globorotalia menardii*, *Globorotalia tumida*, *Globigerinoides sacculifera*) ; in addition it is stated that the carbonate content is about 40 per cent and that coccoliths are abundant. The most plausible explanation of this discrepancy is that MURRAY merely assumed that the calcium carbonate content of this sample was low, being misled by its original description in 1888, by its colour, and by the fact that nearby samples from comparable depths (2570 and 2564 fms, i.e., 4700 and 4690 m) contained practically no carbonate.

Coccoliths and discoasters, determined by Dr. M. N. BRAMLETTE to be Upper Eocene in age (personal communication), account for a large proportion of the calcium carbonate in *Egeria* sounding No. 10. It is possible that Eocene calcareous ooze outcrops at this locality, or it may be thinly covered by the somewhat phillipsitic clay which is the normal Quaternary sediment at depths greater than 2570 fms (4700 m) in this area. It is clearly desirable that highly calcareous sediments collected below the carbonate compensation level should be examined for Tertiary microfossils. Another example of a similar occurrence is a highly calcareous ooze (British Museum registered No. 1959, 42) collected by R.V. *Horizon* on Scripps Institution of Oceanography's ‘ Dolphin ’ expedition from a depth of 2728 fms (5000 m) in the South Pacific at 12° 00′ S, 144° 21′ W. In this core the carbonate content at a depth of 52–56 cm below the sediment surface is 95·5 per cent ; late Tertiary coccoliths

and discoasters, together with a few admixed early Tertiary forms, account for most of this carbonate (microfossils dated by Dr. M. N. BRAMLETTE, personal communication).

The *Planet* sample is not so well documented as *Egeria* sounding No. 10. The German microscopist ALBERT ELGER kindly prepared and allowed us to examine a microscope slide of picked Radiolaria, bearing the locality data mentioned above. These locality data indicate that the sample is from station No. 127 of the *Planet* expedition of 1906–1907 ; this sample is described in the expedition report as *Globigerina* ooze (BRENNECKE, 1909). In addition to Quaternary species, the slide bears some Eocene forms – *Heliodiscus humboldti* (Ehrenberg), *Periphaena decora* Ehr., *Eusyringium fistuligerum* (Ehr.), *Podocyrtis triacantha* Ehr., *Podocyrtis papalis* Ehr., *Anthocyrtium* aff. *hispidum* (Ehr.), etc. There can be little doubt that fossiliferous Eocene occurs at or near the sediment surface in the vicinity of this *Planet* locality.

Although little can at present be determined regarding the conditions of the occurrence of these Eocene microfossils, the findings are recorded in the hope that the sea floor at these localities may be intensively sampled by oceanographic expeditions which will visit the Indian Ocean during the next year or two. It is also desired to draw attention to the necessity of keeping in an orderly and careful way both old (even if there is only a small amount of material available) and recently collected samples from the sea floor : the Tertiary samples noted in this paper were collected 73, 55 and 54 years ago. Because of the cost and difficulty of re-collecting geological samples from remote deep-sea localities, all precautions should be taken to preserve such material, free from any possibility of contamination, in order that it may be reliably used for a number of different types of investigations over a long period of time. Moreover, it is desirable that deep-sea geological samples be indexed geographically, on the basis of a grid of rectangles of 10° of latitude and longitude, as is the collection in the British Museum (Natural History) ; without this index and the facilities of the John Murray Library which has recently been reorganized, *Egeria* sounding No. 10 would not have been re-examined by the authors.

Finally, a word might be said regarding the implications of occurrences of Tertiary sediments at or near the surface of the sea floor. In 1951 one of us (W.R.R.) speculated that the exposure of Tertiary sediments to Quaternary agencies of erosion on the floor of the Pacific was to a considerable extent dependent on Tertiary and Quaternary tectonic movements. This view must be modified as a result of more recent findings. Where biogenous Tertiary sediments are covered by slowly accumulating non-fossiliferous Quaternary clays, the Quaternary cover may be only one or two metres thick. In such areas, no great tectonic movement is needed to expose at least late Tertiary material to agencies of erosion and transportation : this could easily be accomplised by a small slump or a localized current, in an area of relatively low topographic relief.

One of the authors (W.R.R.) wishes to acknowledge financial support from the Trustees of the British Museum, the U.S. Office of Naval Research, and the University of California, which made it possible for him to examine some of the sediment samples in the British Museum (Natural History).

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Contribution from Scripps Institution of Oceanography.

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INSTRUMENTAL NOTE

A modification to the T. S. Ekman-Merz current meter

(*Received* 20 *June* 1960)

THE Eckman-Merz current meter as manufactured by the Tsurumi-Seiki Co., Ltd. is of excellent construction but has one minor defect : it is easily possible to place the compass box in the meter backwards.

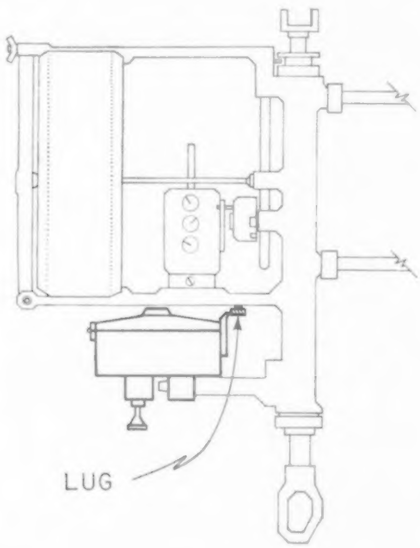

FIG. 1.

This source of error can be eliminated by installing a lug on the underside of the frame which supports the counting mechanism. The lug should be placed in such a position that when one attempts to put the compass box in backwards, the upright locking spring on the cover of the box strikes the lug before the box is in clamping position. When the box is properly inserted, on the other hand, its low hinged side easily clears the lug.

A Fillister-head machine screw set in a tapped hole makes a very satisfactory lug.

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LETTERS TO THE EDITORS

The Line of Zero Set

(*Received* 28 *June* 1960)

WHEN electrodes are towed in tandem from the stern of a ship under way the G.E.K. (geomagnetic electro-kinetograph) senses the transverse component of water motion or set of the ship. When the indicated rate of transverse motion is reduced to zero the ship can be said to be steaming on a course which is parallel to the local surface current direction in either the upstream or downstream sense. If, while tracking the current, the position of the ship is determined at regular intervals by means of some radio-navigational aid, a line is generated on a chart which reflects certain properties of the flow. This line, in an accelerated system, does not fall within any of the existing hydrodynamic classifications : streamline, streak-line, or path-line. But it may be considered that the *line of zero set* has a family resemblance to these more conventional concepts, and could be a useful index in natural situations where the field of surface motion is otherwise undetermined.

The operational principles of sailing a line of zero set were mentioned by the writer in 1951 (VON ARX, 1951) but an actual field trial of the method was not made until there was need, during the April–June 1960, multiple ship survey of the Gulf Stream, to delineate the courses of flow between several parallel lines of oceanographic stations. During this cruise the convolutions of the main current of the Gulf Stream were tracked for a distance approaching 2100 nautical miles between Longitudes 49°–69°W. The results of this experiment will be reported in another place.

It was found that steering a line of zero set was most easily accomplished where the currents were strong. (When the indicated current speed fell below 25 cm/sec it was perhaps the current itself that became sufficiently irregular in direction to make tracking difficult). Where the current speed was in excess of 50 cm/sec, tracking was always practicable provided the zero point of the electrodes could be determined at intervals of about an hour. During both tracking and zero point operations the ship could move through the water at the highest speed suited to existing weather conditions.

During the recent cruise it was possible to observe the depth of certain key isotherms as indicated by thermistor beads towed at the surface and 100 m levels on a thermistor chain. (W. S. RICHARDSON and C. J. HUBBARD, 1960). When the ship was tracking the band of highest surface velocities the 15 °C isotherm tended to remain at or near a depth of 100 metres below the keel. This relationship between the depth of key isotherms and the position of the maximum current gave some assurance that the line of zero set was being followed except where there were pronounced convolutions in the course of the current, or apparent breaks in its continuity. On several occasions the line of zero set led the ship into a region of weak but strongly curved currents. A transverse search in these areas revealed no strong or well defined currents nearby but rather a broad area of degenerate motion which re-organized itself into a strong current downstream and several tens of miles nearer the coast. These features seem to have been associated with shallow (100 to 200 metres deep) floods of Gulf Stream water into the region normally occupied by Slope Water.

Two other effects tended to lead the ship out of mid-stream. One was due to the influence of beam winds and seas which caused the cable to tow at an angle to the keel. This had to be corrected by deliberately crabbing upwind. The other effect was related to the divergent motion of surface water from the current maximum in the Gulf Stream. The band of maximum surface velocity is normally only a few miles wide. On the left of the current maximum the current seemed to often possess a relatively strong transverse component of flow toward Slope Water which with frontal sinking probably accounts for the tendency for organic films and even large forms of flotsam to collect at the surface outcrop of the frontal interface. Airplane observations of the motions of fluorescein dye markers placed in a line at right angles to the frontal outcrop show that Gulf Stream Water to the left of mid-stream flows toward Slope Water at rates as high as 20 cm/sec. A ship steering down-

stream on a line of zero set may follow this flow and find itself running to the left of the band of maximum current into the region of weaker currents near the frontal outcrop.

Conversely, were the ship to follow a line of zero set against the current it is presumed, but not yet demonstrated, that the course might tend to be led into the band of maximum velocity, provided that the surface motion diverges from the band of maximum current. It is possible, of course, that the surface motion toward the frontal outcrop is not associated with divergence in mid-current but rather with transverse flow across the full width of the Gulf Stream.

Lines of zero set were steered as follows : (1) the zero point of the electrodes was measured hourly by the conventional manoeuver of turning the ship through 90° to its base course and returning to base course through a 180° turn and a final 90° turn so as to present the electrodes to the longitudinal component of flow in the direct and the reverse senses. The average of the two readings at right angles to base course was taken as the zero point of the electrical system. From the signals observed on base course and at right angles to base course the current speed and direction were determined in the usual way. (2) With knowledge of both zero point and local current direction the ship was then steered downstream, which caused the electrical signal to coincide with the zero point. Small corrections of heading were then applied as the signal showed signs of departing from electrical zero.

This procedure can be followed on either upstream or downstream sailings. When the ship is headed downstream in a current of speed C and a transverse set S is noted, it is possible to correct the course by an angle whose tangent is S/C. The sense of this correction depends on the heading :—

Downstream, correct port set by turning to port

Upstream, ,, ,, ,, ,, ,, ,, starboard.

Under ordinary circumstances course changes of a few degrees are required several times each hour to keep the ship on the line of zero set.

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Contribution No. 1125 *from the Woods Hole Oceanographic Institution.*

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The occurrence of the wahoo in the Northwest Atlantic

(*Received* 8 *September* 1960)

THE wahoo, *Acanthocybium solanderi* (Cuvier) (FIG. 1), a pelagic fish, is known to be widely distributed in the tropical waters of the world (BRIGGS, 1958). Available information concerning the distribution of this species indicates that it is generally found in the vicinity of land masses or reefs. MATHER and DAY (1954) have recorded the capture of this species in the offshore waters of the tropical Atlantic, and SPRINGER and BULLIS (1956) have noted 21 locations where wahoo have been recorded in the Gulf of Mexico and Caribbean Sea. Wahoo have been taken from the waters surrounding the Bermuda Islands (MOWBRAY, 1956), and, during the warm months of the year, have been reported occasionally by sportfishermen in the coastal waters south of New England (personal communication from FRANK J. MATHER III).

Information on the offshore occurrence of this species in the northwestern Atlantic has become available as a result of pelagic fishery explorations carried out by the U.S. Bureau of Commercial Fisheries between 1957 and 1960. During this period, 111 sets were made using modified Japanese-style long-line fishing gear (CAPTIVA, 1955) between the latitude of the Grand Bank and the latitude of the Bermuda Islands (FIG. 2).

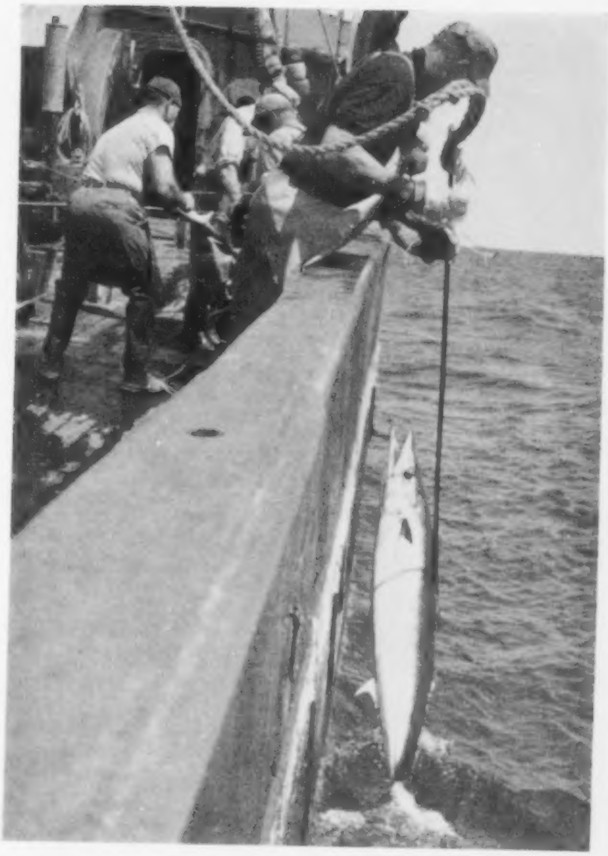

FIG. 1. A wahoo, *Acanthocybium solanderi* (Cuvier) being landed aboard the M.V. *Delaware*. This fish was a female 153·9 cm. long (fork length) and weighed about 60 pounds. The location of this capture on long-line gear was 40° 28′ N. lat., 62° 29′ W. long.

Twenty-one wahoo were recorded in the course of the long-line operations from 15 offshore locations (Table 1). The majority of these captures were made in the general vicinity of the Gulf stream at locations where the surface water temperatures ranged from 71·8 °F (22·1 °C) to 83·0 °F

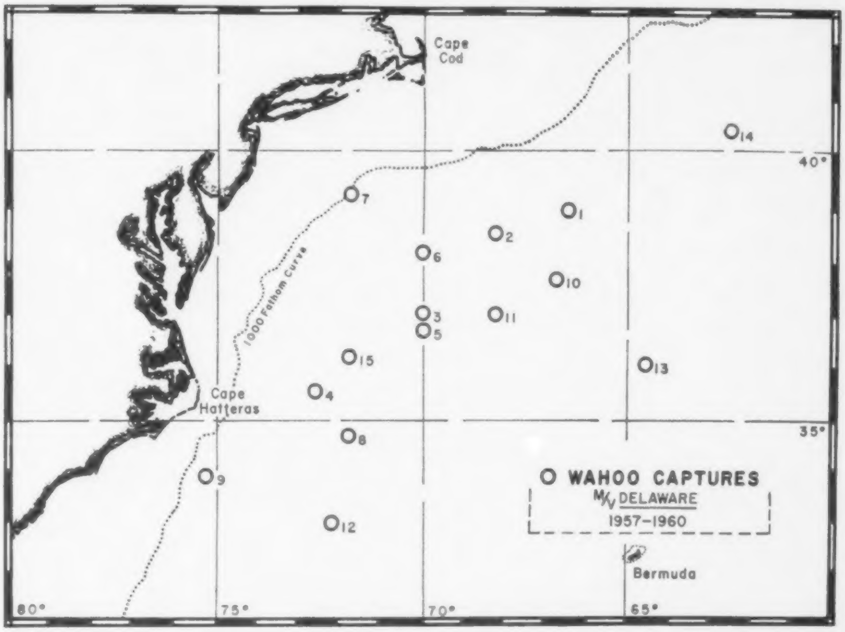

Fig. 2. Locations in the Northwest Atlantic at which wahoo were captured by long-line gear. Circles indicate approximate position of captures, numerals refer to locations listed in Table 1.

Table 1. Wahoo catches in the Northwest Atlantic 1957–1960, *M.V.* Delaware.

Date	*Lat. N.*	*Long. W.*	*Map Location*	*Surface Temp.* °F. (°C)	*Number Caught*
9 June, 1957	38° 58′	66° 26′	1	72·5 (22·5)	1
12 June, 1957	38° 35′	68° 12′	2	79·0 (26·1)	1
27 June, 1957	37° 02′	70° 00′	3	78·0 (25·5)	2
30 July, 1957	35° 53′	72° 35′	4	83·0 (28·3)	1
3 Oct., 1957	36° 42′	70° 00′	5	78·0 (25·5)	3
4 Oct., 1957	38° 12′	70° 00′	6	73·0 (22·8)	1
7 Oct., 1957	39° 17′	71° 49′	7	72·0 (22·2)	1
9 Oct., 1957	36° 15′	71° 49′	8	77·0 (25·0)	4
10 Oct., 1957	34° 45′	71° 49′	9	77·0 (25·0)	1
16 Oct., 1957	33° 55′	75° 13′	10	81·2 (27·3)	1
12 July, 1958	37° 42′	66° 42′	11	79·5 (26·4)	1
13 July, 1958	37° 03′	68° 14′	12	82·0 (27·8)	1
25 July, 1958	33° 06′	72° 10′	13	81·5 (27·5)	1
5 May, 1960	40° 28′	62° 29′	14	71·8 (22·1)	1
1 Aug., 1958	36° 05′	64° 32′	15	82·5 (28·0)	1

(28·3 °C). The wahoo records listed by Springer and Bullis (1956) were accomplished at locations where a strikingly similar range of surface temperatures was observed ; 71·0 °F (21·6 °C) to 85·0 °F (29·4 °C). The four wahoo catch records provided by Mather and Day (1954) were also from positions at which the surface temperatures fell within the temperature ranges noted above.

All captures reported on herein were made between the months of May and October, although considerable fishing effort was expended during the cooler (November–April) months.

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JAMES L. SQUIRE, JR.

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An historical note

(*Received* 15 *October* 1960)

THE VERY interesting note by J. D. ISAACS (Deep-Sea Res. 7, (1) pp. 61–67) on modern devices for releasing instruments (dropped to the bottom of the ocean) by gradual dissolution of a link connected to the anchor, and its reference to earlier papers describing instruments released by dissolving salt-blocks, reminds me of once having encountered a reference to them of great antiquity. In Aristotle's theory of dreams (DE SOMNIIS, 461b, 15–17), the succession of sensory images which he suggests occurs more or less automatically during sleep, and accounts for dreams, is enlikened to ' the artificial frogs in water which severally rise (in fixed succession) to the surface in the order in which the salt (which keeps them down) dissolved.

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HENRY STOMMEL

BOOK REVIEWS

T. F. Gaskell : **Under the Deep Oceans.** Eyre and Spottiswoode, 1960. 237 pp. 25/-.

Popular science is difficult to write. The average reader wants an interesting book which is easy to read but the scientist demands complete accuracy. Dr. Gaskell goes a long way towards achieving this combination. Throughout the book there is the story of H.M.S. *Challenger's* expedition round the world in 1950–52, in which the author played a leading part. This is used to connect descriptions of the various types of scientific work which was carried out. The book begins with an outline of modern geophysical methods of exploring the deep oceans, and goes on to describe what has been found out and how it was done. There are numerous amusing and personal touches which make even the descriptions of scientific experiments easy and pleasant to read.

Dr. Gaskell is to be congratulated on having written a popular book which can be read with pleasure, even by a scientist. His enthusiastic personality is sprinkled on every page. I thoroughly enjoyed reading it.

B. C. Browne

J. A. Colin Nicol : **The Biology of Marine Animals.** Pitman. 707 pp. 95/-.

This is a remarkably useful book. It is clearly written and well indexed, and covers a great variety of biological topics about marine animals. It begins with a study of the physical external environment and goes on to the internal environment of the body fluids, respiration, feeding and digestion and excretion. There are good chapters on sense organs, the nervous system, effector mechanisms, and the book finishes by a discussion of the associations of marine animals and curious and interesting comparative physiology and skeletal structures. The book is well illustrated and there are good and extensive selections of references. Within the physiology and physiological ecology of marine animals there is scarcely a topic to which the reader cannot turn for a concise summary and a remarkably interesting comment. One could confidently recommend it to University students in Zoology and Physiology, as well as those who are particularly interested in marine animals.

C. F. A. Pantin

ERRATA

L. A. Zenkevitch and J. A. Birstein : On the problem of the antiquity of the deep-sea fauna. *Deep-Sea Res.* 7, 1, pp. 10–23.

For Spirula read Spinula throughout

Page 14, line 15 from the bottom ; 200 and 300 should read 2000 and 3000 m., line 23 from the bottom ; 600 should read 6.

Page 15, Table 1 ; columns 3 and 4 should read below 2000 m and below 3000 m.

Page 17, line 2 from top ; Soldia, Soldiella should read Joldia and Joldiella.

Page 19, line 16 from top ; Andraishev should read Andriashev.

Page 23, line 10 from bottom ; *Biogocehim* should read *Biogeochim.*

Micro-organisms as hydrological indicators in seas and oceans—IV

The Hydrological Structure of the Atlantic Ocean, including the Norwegian and Greenland Seas, based on microbiological data

A. E. KRISS, I. N. MITZKEVITCH, I. E. MISHUSTINA and S. S. ABYZOV

Abstract—The quantitative distribution of heterotrophs in the water column of the Atlantic Ocean between Greenland and the Tropic of Capricorn (along 30°W), in the Norwegian, and in the Greenland Seas was studied. In the tropics the abundance of micro-organisms which assimilate slightly decomposed, non-humus organic matter is great, while in the subarctic and arctic areas it is low.

Equatorial-tropical water, rich in heterotrophs, was identified in the subtropic and subantarctic zones of the Atlantic Ocean, in the Norwegian and in the Greenland Seas at various depths. It occurred not only down to 1000 m but also much deeper at 2000–2500–3000 m.

Judging by the finding of equatorial-tropical water layers or ' islands ' in the Atlantic Ocean, in the western Norwegian Sea and in the Greenland Sea at the same levels, it may be supposed that the circulation of these waters at certain depths is stable over extensive areas.

Most of the Atlantic Water (along 30 °W) from Denmark Strait to the Tropic of Cancer, is of arctic origin, i.e., water with few heterotrophs. These waters penetrate into the tropics and cross the equator. However, in the equatorial-tropical zone they do not form as thick a layer as DEFANT (1957) estimates.

Microbiological data indicate that waters in the equatorial-tropical zone of the Atlantic are significantly enriched by slightly decomposed, non-humus organic matter. In this respect they are similar to the *Equatorial Water Masses* of the Indian and Pacific Oceans. They, therefore, cannot be considered as merely transitional between the *Central Water Masses* of the northern and southern Atlantic.

IN THE open Atlantic Ocean deep-sea microbiological investigations have been conducted by CERTES (1884), FISCHER (1894), CHUN (1899), OTTO and NEUMANN (1904) and GAZERT (1912), as well as by LEVIN (1899) in the Greenland Sea. These investigations showed that the numbers of heterotrophic micro-organisms which will grow on albuminous media fluctuates within a wide range depending on the depth and the geographic location.

For a more detailed account of the microbial distribution, water samples were taken from the surface down to the ocean bottom on all hydrological stations on the *Ob* (1956) in the Greenland Sea, on the *Sevastopol* (1958) in the Norwegian Sea, and on the *M. Lomonosov* (1959) in the Atlantic Ocean. In the Atlantic, investigations were carried out at 41 stations along 30 °W from 66 °N down to the Tropic of Capricorn. In the Norwegian Sea there were four sections with 51 stations between the Scandinavian Peninsula and Iceland or Jan Mayen. In the Greenland Sea 34 stations were chiefly located on three latitudinal sections along 78°, 79°, and 80° N (Fig. 1). At six stations in the Atlantic Ocean, eight in the Norwegian Sea and seven in the Greenland Sea microbiological analyses of the sediment surface layer were also carried out.

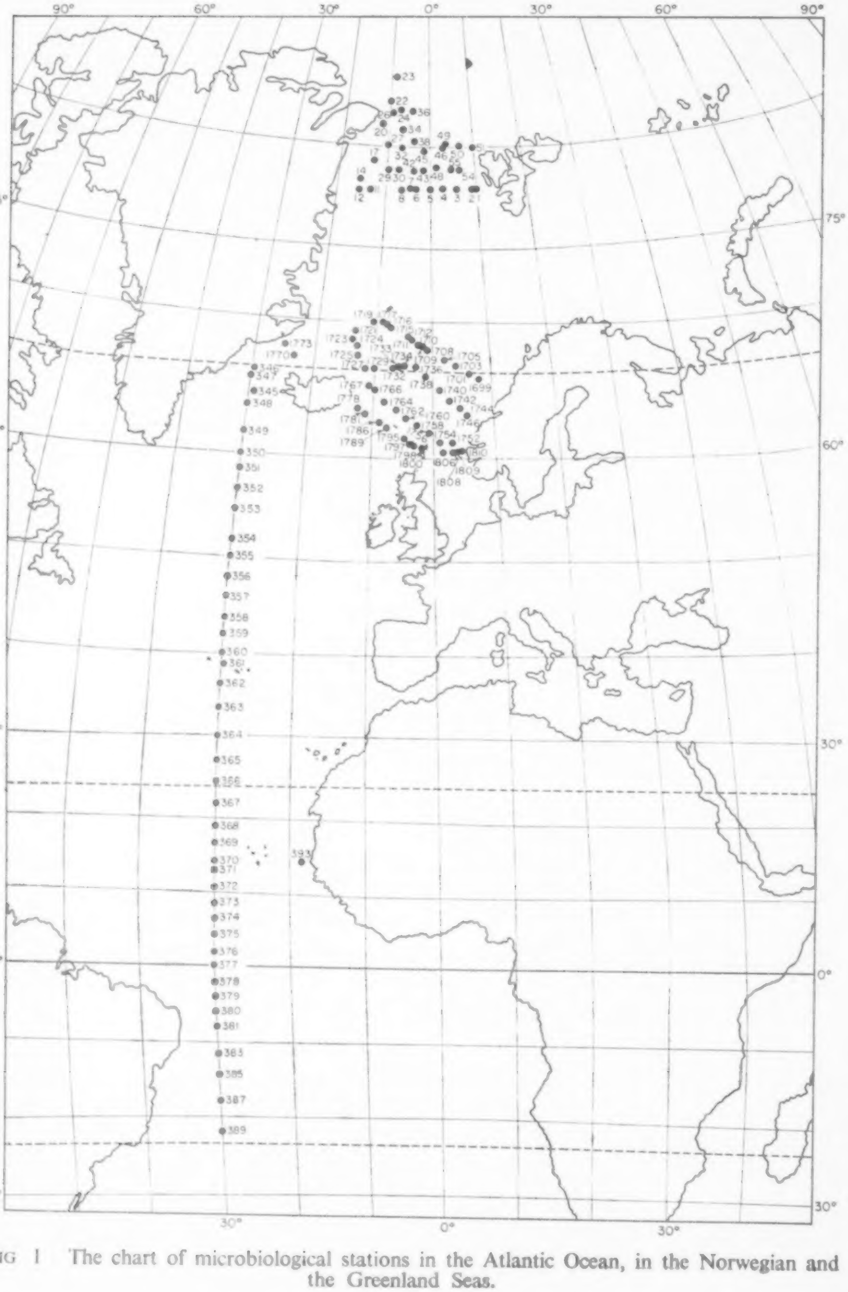

FIG 1 The chart of microbiological stations in the Atlantic Ocean, in the Norwegian and the Greenland Seas.

METHODS

Sampling for microbiological analyses was carried out with a Nansen water bottle at each station at the following standard levels : 0 ; 10 ; 25 ; 50 ; 75 ; 100 ; 150 ; 200 ; 250 ; 300 ; 400 ; 500 ; 600 ; 750 (or 800) ; 1000 ; 1500 ; 2000 ; 2500 ; 3000 m and deeper at thousand-metre intervals. In some cases samples were also taken at intermediate levels. Water samples of 40 ml taken with all due precautions were immediately analysed in the laboratories on board ship by the method of growing micro-organisms on membrane ultrafilters (KRISS, 1959). After filtration, membrane ultrafilters No. 2 were put face up on nutrient agar in order to culture the microbial cells deposited on the ultrafilter. Samples of mud in dilutions of 1 : 10 were seeded on nutrient broth (taking 0·5 ml of each dilution) and on nutrient agar (taking 0·25 ml of the mud dilution 1 : 10). The nutrient media were prepared with ocean water. After incubation of 4–7 days at 18–35 °C, the colonies were counted and individuals of dissimilar colonies were separated and placed on agar slants using the same media as for the original culture. All in all, 1733 water samples were analysed in this way.

RESULTS

As for the Antarctic Ocean (KRISS, LEBEDEVA and MITZKEVITCH, 1958), the whole water column in the high latitudes of the Atlantic, with the exception of a few layers has few heterotrophs. Most water samples yielded single colonies or the filters were sterile. This was observed at the stations located between 70° and 40 °N (Fig. 2).*

Table 1. *The correlation of heterotrophs from different geographic areas of the Atlantic Ocean, and in the Norwegian and Greenland Seas. The figures are the percentage of water samples containing a given number of colonies correlated with the total number of samples analysed.*

Latitudes	*Number of samples analysed*	*Number of colonies on filters*		
		0–9	10–99	*over* 100
Atlantic Ocean				
22 °S – 11 °S	81	2·5	20·0	77·5
8 °S – 8 °N	167	3·0	20·0	77·0
10 °N – 21 °N	121	1·6	33·9	64·5
24 °N – 38 °N	104	44·3	38·4	17·3
40 °N – 48 °N	88	90·0	10·0	0
50 °N – 58 °N	78	98·7	1·3	0
60 °N – 66 °N	71	95·7	4·3	0
Norwegian Sea				
60 °N – 70 °N	575	35·0	54·0	11·0
60 °N – 65 °N	203	14·9	57·6	27·5
64 °N – 70 °N	372	46·6	51·6	1·8
Greenland Sea				
78 °N – 83 °N	448	78·8	16·5	4·7

In the subtropical area (40 °–23 °N), the heterotrophs in the water mass increased as in the Pacific Ocean (KRISS, ABYZOV and MITZKEVITCH, 1960) and in the Indian Ocean (KRISS, LEBEDEVA and MITZKEVITCH, 1960a) and reached their greatest abun-

*In Fig. 2 and in all similar figures, whenever the 40 ml sample was sterile, the dots were placed on the ordinate to make the graphs less complicated (lg0 = – ∼).

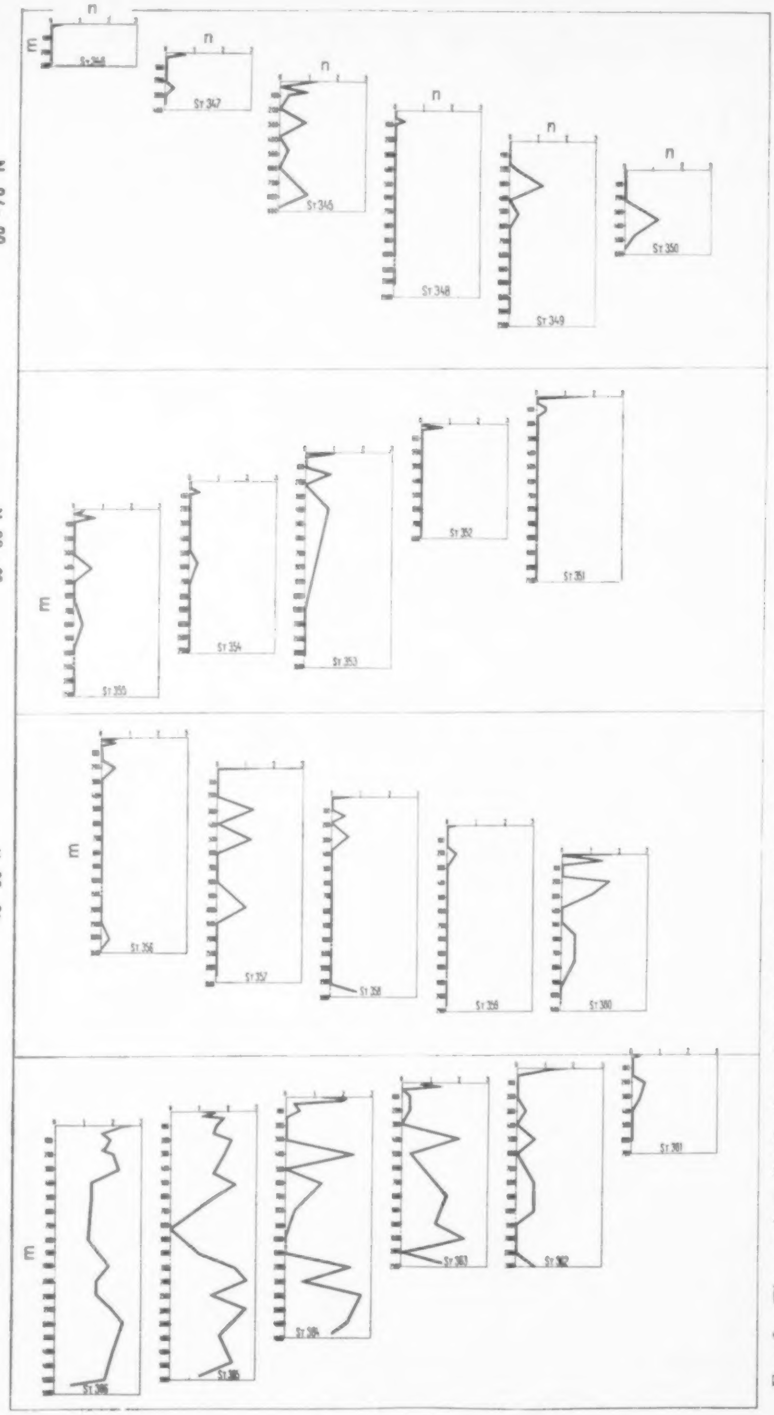

FIG. 2. The vertical distribution of heterotrophs at stations in the Atlantic Ocean between 70 °N and the Tropic of Cancer (*n* equals log of the number of bacteria per 40 ml of water).

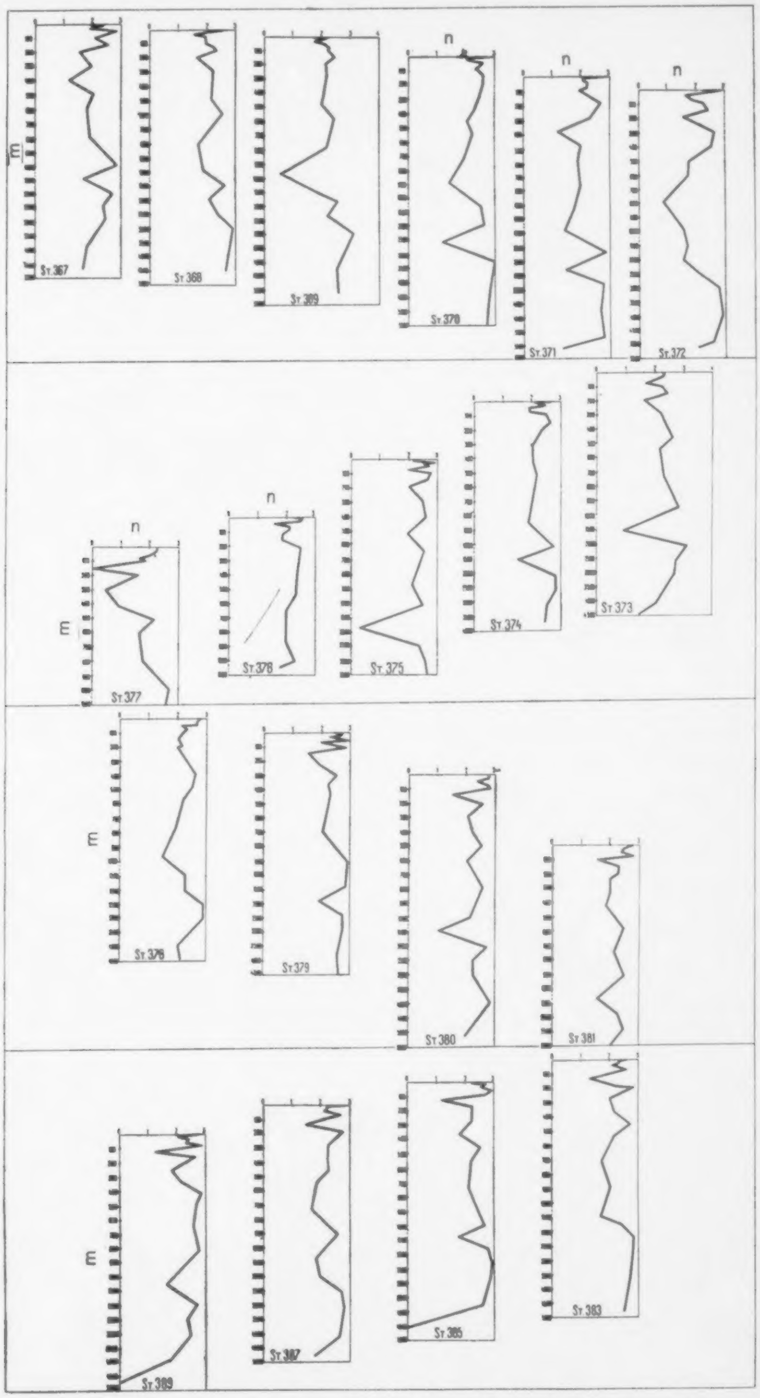

FIG. 3. The vertical distribution of heterotrophs at stations in the Atlantic Ocean between the Tropic of Cancer and the Tropic of Capricorn (n equals log of the number of bacteria per 40 ml of water).

dance in the tropical equatorial zone. In this part of the Atlantic, water samples taken from the surface down close to the bottom, with few exceptions contained hundreds of heterotrophs (Fig. 3).

Regularity in the distribution of the microbial population (heterotrophs) in the Atlantic appears to be geographically quite distinct as shown by the correlation for different latitudes between water samples rich and poor in heterotrophs (Table 1). In the transition between the tropic and equatorial zones, the percentage of the samples with great numbers of heterotrophs decrease significantly while the percentage of samples with few of these micro-organisms increases markedly. The Greenland Sea (Fig. 4) and particularly the Norwegian Sea (Fig. 5) have quite a different heterotroph content from the subarctic portion (along 30 °W) of the Atlantic. Of the 575 water samples from the Norwegian Sea 65 per cent had relatively great numbers of heterotrophs, thus approximating the subtropic zone of the North Atlantic (Table 1). There is, however, a sharp difference between the southern and northern Norwegian Sea : 27 per cent of the water samples from the southern sections contained more than 100 colonies, while only 2 per cent in the northern portion were as rich in heterotrophs. Undoubtedly, the Gulf Stream contributes greatly to the peculiarities of the Norwegian Sea.

In the Atlantic Ocean and in the Norwegian and Greenland Seas 1 g of wet mud contained dozens, hundreds and less often, thousands of heterotrophs.

A comparison of the results in the Atlantic with those in the Indian and Pacific oceans suggests a definite geographic zonation in the world ocean distribution of heterotrophic microbes. The significance of these microbic forms is that their quantitative distribution in seas and oceans is a measure of the distribution of organic matter which has not yet been transformed into humus and is fairly available to hydrolytic enzyme action. It seems quite evident that in high latitude of the world ocean (arctic, antarctic, subarctic and subantarctic) the density of the microbe population is insignificant. Although these areas are richest in phytoplankton productivity, the products of metabolism and the plant remains do not provide a great food supply for heterotrophs.

The heterotrophs are strikingly abundant in the equatorial and tropical zones of the Atlantic, Indian and Pacific oceans where investigations have been carried out. It seems paradoxical that great numbers of microbes (heterotrophs) occur in the world ocean in areas where plants and animals are scarcest. Thus, while the heterotrophic content in the world ocean increases from the Polar regions toward the equator, the reverse is true for other forms of life (ZENKEVITCH, 1951). This might be explained by the fact that in tropical areas the chief materials supporting an abundance of microbes is only slightly, not fully, decomposed organic matter of an allochthonous nature. It is quite evident that in the equatorial-tropical zone the abundance of this organic matter in the water is much greater than that of analogous autochthonous and allochthonous organic forms in high latitudes.

In the equatorial–tropical zone of the Pacific and Indian oceans, the enrichment of waters by organic matter which is readily accessible to the hydrolytic fermentation of micro-organisms, is believed to occur in the Coral Sea and in the region of the Australasian Archipelago. In the Atlantic ocean, the increased abundance in the tropical waters of organic matter which has been only slightly decomposed seems to be due to the effluent of such large rivers as the Amazon, the Orinoco, the Congo and

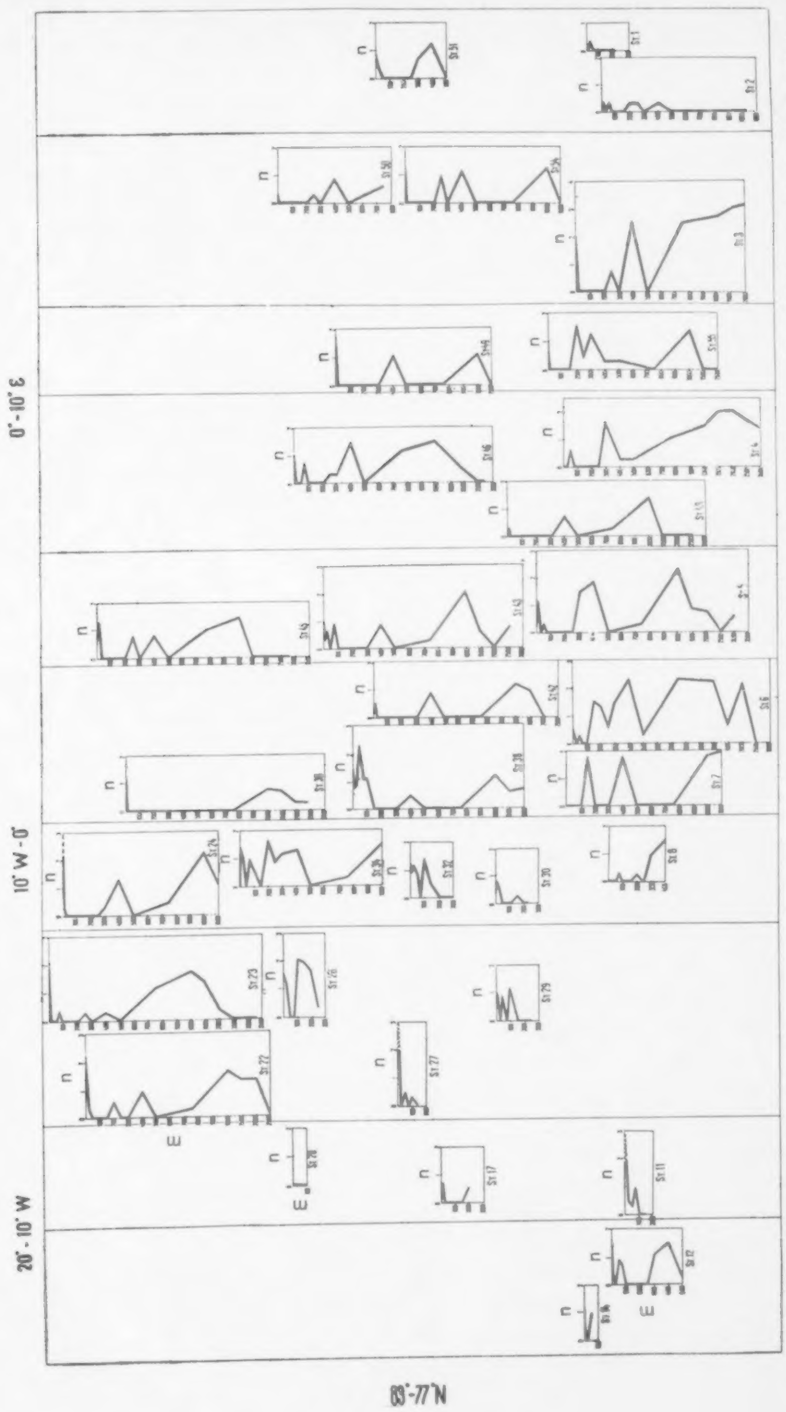

FIG. 4. The vertical distribution of heterotrophs at stations in the Greenland Sea (*n* equals log of the number of bacteria per 40 ml of water).

the Niger, with their catchment areas covering extensive expanses of the equatorial regions which are densely populated by plants and animals. Other sources for allochthonous organic matter are the numerous islands of the Carribean Sea into which the equatorial current branches enter. In this connection, Kolbe's (1957) record of fresh-water diatom frustules in the sediments of the equatorial Atlantic are especially interesting. In bottom samples, taken thousands of kilometres off the African coast, he found more than a thousand valves of fresh-water diatoms per slide. Taking into consideration the great distance from land, the great ocean depths and the numbers of diatom frustules, one must not underestimate the effect of river effluent from equatorial Africa, driven even further by the trade winds, in the content of organic and inorganic matter in the equatorial–tropical waters of the Atlantic. Terrigenous organic substances from the African coast are also carried to the waters of the North and South Equatorial Currents (15 °N to 5 °S) by strong northwest winds which carry clouds of dust so dense as to limit visibility to 1–2 kilometres and at times, even to 150 metres.

Equatorial-tropical waters enriched by organic compounds easily assimilated by micro-organisms are found in subtropic and subarctic zones of the Atlantic where they have been transported by currents. Four clear-cut layers of this water were observed in the subtropical zone (23 °–40 °N) at : (1) 10–25 m, at (2) 50–75 m, 75–100 m, 100–150 m, 200, 300 m, at (3) 350–450 m, 540–500 m, 600–750 m, and at (4) 400–600 m, 600–750 m, 800–950 m, 850–1000 m. A fifth layer was identified as far north as 35 °N at 1000–2000, 1750–2250 and 1500 m. To the north between 40° and 66 °N the continuation of these layers or ' single water islands ' of equator-tropical origin were found at depths of 10 to 1000 m. At two stations the increased heterotroph content was determined in the 2500–3000 m layer (Figs. 2 and 6).

The waters along the section along 30 °W from Denmark Strait to the Tropic of Cancer contain extremely few heterotrophs throughout the whole water column. The scarcity of slightly decomposed, non-humus organic matter is evidence of the pronounced influence of Arctic waters in that part of the Atlantic. These waters penetrate into the tropics as well. A layer with few heterotrophs was found between the Tropic of Cancer and the Tropic of Capricorn at depths of 1500 ; 750–1000 ; 850–1250 ; 700–950 ; 1000–1500 ; 1250–1750 ; 1500–2250 ; 2000 ; 1000–1750 ; 1000–1500 ; 1250–1750 ; and 1000–1500 m (Figs 3 and 6).

It is important to note that the microbiological data agree well with DEFANT's hydrographic data. However, the layer is not as thick in the tropics as that estimated by DEFANT (1957). Hitherto it was not quite certain whether this layer containing few organic compounds which are easily assimilated by micro-organisms was of arctic origin only.

Considering that, according to DEFANT's data, subantarctic waters cross the equator at depths of 1000–2000 metres and are found as far north as 20 °N, one can assume that in the equatorial-tropical zone, waters with few heterotrophs are, to a certain extent, of mixed arctic-antarctic or arctic-subantarctic origin.

In addition to waters from high latitudes at depths of 750–2250 m in the tropical Atlantic there are less clear-cut layers with few heterotrophs at 25, 50, 75 m and 100–150 m. In the southern tropics these layers extend from 23 °S almost to the equator. A comparatively thick layer of antarctic water occurs near the bottom between the Tropic of Capricorn and 13–14 °S.

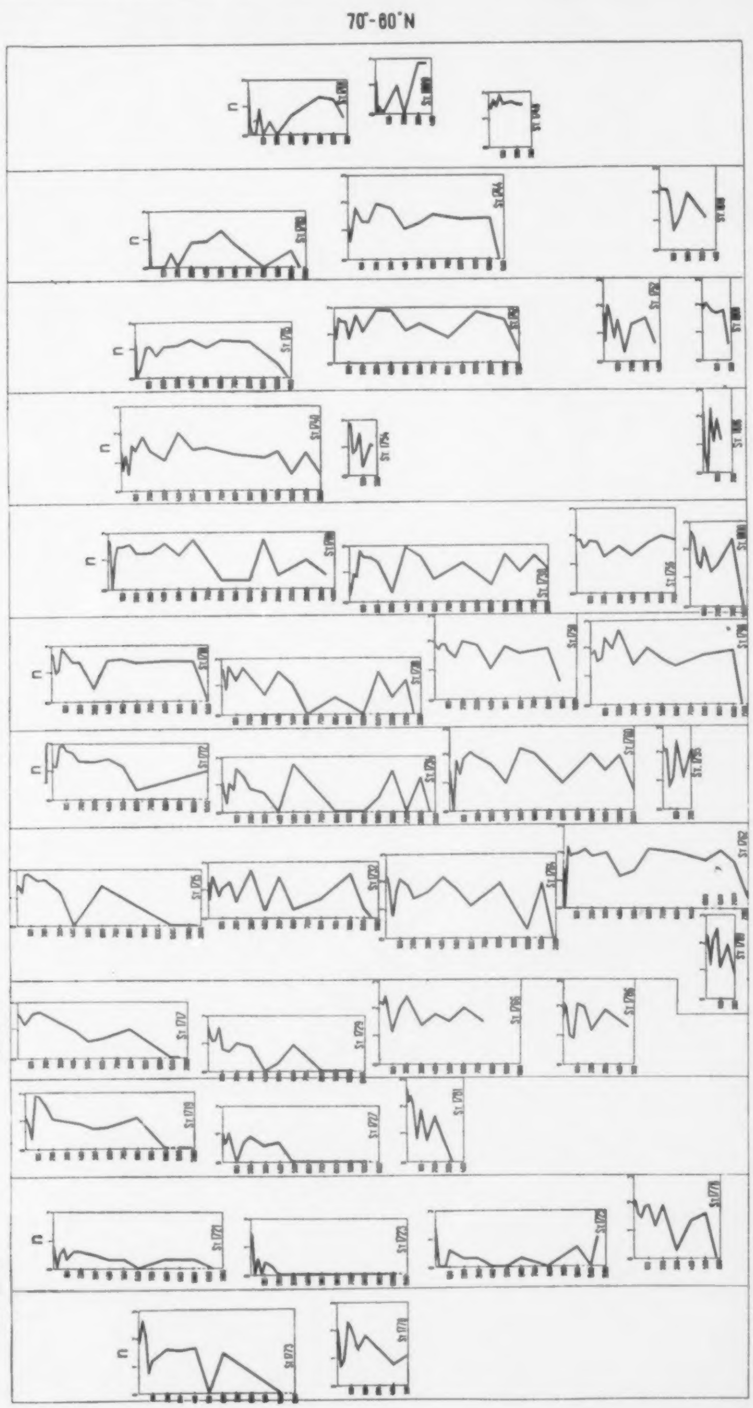

FIG. 5. The vertical distribution of heterotrophs at stations in the Norwegian Sea (*n* equals log of the number of bacteria per 40 ml of water).

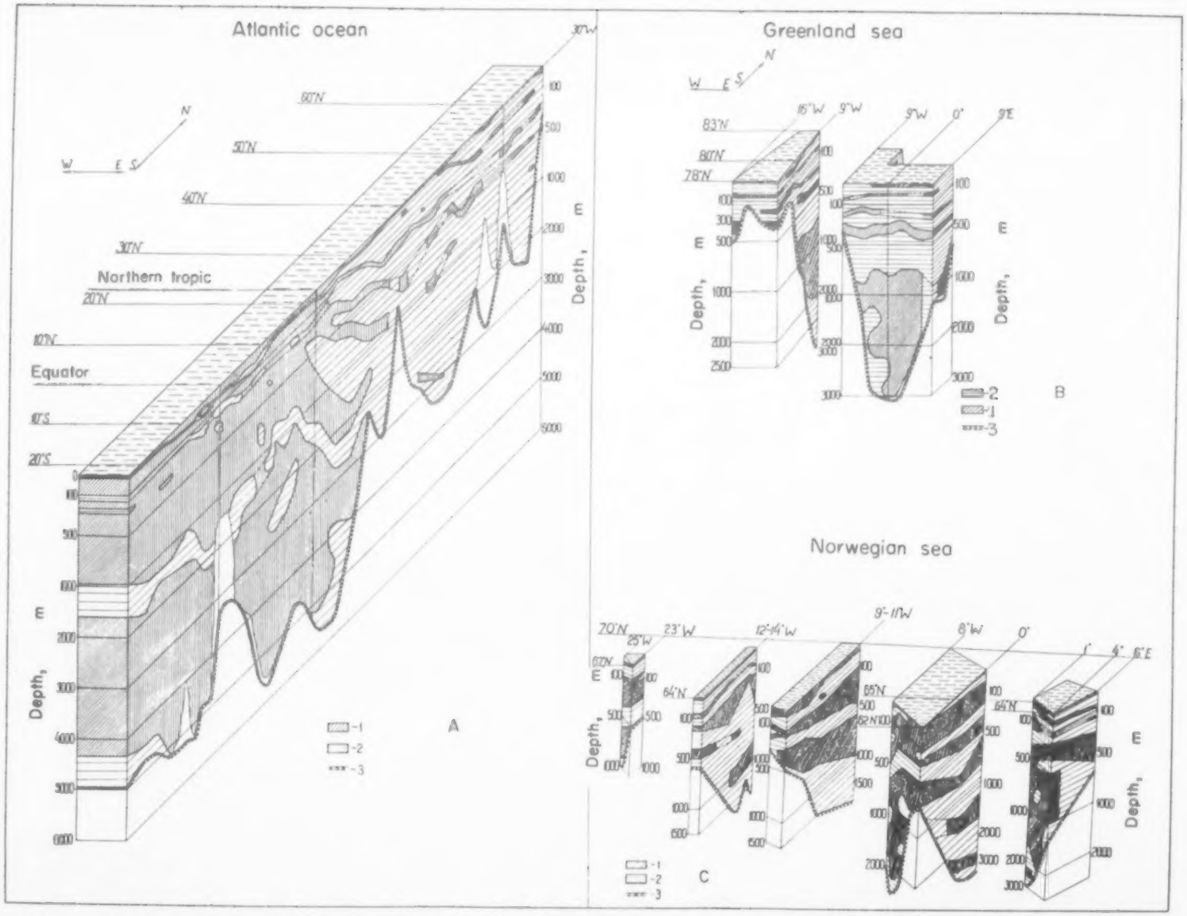

FIG. 6. Hydrographic structure of the Atlantic Ocean, the Greenland Sea – and the Norwegian Sea based on microbiological data. 1—water layers of equatorial-tropical origin with a high bacterial count; 2—water layers of arctic or antarctic origin with low bacterial count ; 3—bottom A. Atlantic Ocean, B. Greenland Sea, C. Norwegian Sea.

Like the subarctic Atlantic, the water mass in the Greenland Sea (between 78° and 83 °N) is of arctic origin. However, at some depths there are layers with a relatively abundant heterotroph count. These suggest that branches of the North Atlantic current transporting equatorial-tropical water penetrate this area (Figs. 4 and 6). The layer with an abundance of heterotrophs occurred at nearly all stations, except in shallow water and at station No. 36, at a depth of 300–400 m. With the transition from 78 °N to 83 °N the number of heterotrophs in this layer decreases. However, their abundance is still much greater than in layers either above or below this.

It is interesting to note that in the Greenland Sea fairly well defined water layers of equatorial-tropical origin exist at depths of 750–1000–2000 m. In some places these extend down to 3000 m close to the bottom ; in others arctic water flows between this layer and the bottom. At some stations branches of the North Atlantic current were identified at depths of 150–200, 200–250 m and also closer to the surface.

The hydrography of the Norwegian Sea is more complicated. Branches of the East Greenland and the North Atlantic currents alternate both at the surface and at great depths (Fig. 6). However, at almost all deep stations arctic water occurs near the bottom. Down to 1000 m the bulk of waters of equatorial-tropical origin was located at the stations between 0° and 8 °W. These stations were close to the main flow of the North Atlantic current. From microbiological data it is evident that the influence of equatorial-tropical waters in the Norwegian Sea is not confined to depths of 1000 m only. Fairly thick water layers with increased amounts of organic matter easily assimilated by micro-organisms occur much deeper at 1000–2000 m and 2000–3000 m (Figs. 5 and 6).

It should be noted that there are water layers or ' islands ' of the equatorial-tropic origin in the Greenland and Norwegian (12°–14 °W) Seas and in the Northern Atlantic (along 30 °W) at the depths of 300–400–600 and of 750–1000–1500–2000 m. Possibly, at these depths the circulation of this water is fairly stable and covers an extensive area of the Northern Atlantic Ocean, the Greenland Sea and the western part of the Norwegian Sea.

Microbiological data do not support the widely held viewpoint that *Equatorial Water Masses* (SVERDRUP, JOHNSON and FLEMING, 1957) are absent in the Atlantic Ocean, in contrast to the Indian and Pacific Oceans where such water masses do occur in the tropics. Since the waters in the equatorial-tropical Atlantic are markedly rich in slightly decomposed non-humus organic matter, it is evident that these waters have peculiarities distinguishing them from other water masses. Hence, it is hardly possible to consider these waters as merely transitional between the heterogeneous *Central Water Masses* of the northern and southern Atlantic. Rather, we believe that, as a result of significant changes the equatorial Atlantic waters acquire some peculiarities, similar to a certain extent to those of the *Equatorial Water Masses* in the Pacific and Indian oceans.

Currents transporting equatorial-tropical waters to the highest latitudes are responsible for the distribution of terrigenous organic matter throughout the entire water mass of the world ocean. Considering the abundance in these waters of heterotrophs which mineralize organic matter, one should not underestimate the role of allochthonous organic compounds as a source of substances which determine the productivity of a water mass.

It is also suggested that deep ocean currents which transport equatorial-tropical waters are not as slow as was hitherto believed. Otherwise it would be hard to explain the presence – in the deep layers in temperate latitudes and in higher latitudes – of such an abundance of easily decomposed organic matter, an abundance which causes so significant a heterotroph content there

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Nitrogen/argon and nitrogen isotope ratios in aerobic* sea water

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Abstract—Various factors which influence the concentrations of gases dissolved in sea water are discussed. A surface equilibrium model is proposed, and results presented to test the model and to ascertain whether or not nitrogen dissolved in sea water is biologically and chemically inert. The method utilized argon as a reference gas, with a mass spectrometer as the primary analytical tool. The conclusion is reached that within $\pm$ 1 per cent the model is applicable and nitrogen is 'conservative.' The possible implications of apparent small differences between the predictions of the model and the experimental results are discussed. There is some evidence that the nitrogen 29/28 relative abundance in the dissolved gas may be greater than that in the atmosphere by approximately one part in 10,000.

INTRODUCTION

VARIATIONS in the percentage saturations** of nitrogen and the inert gases dissolved in sea water have been reported by several workers. BUCH (1929) found a range of 93 to 111 per cent for the combined nitrogen and inert gas content.†† Nitrogen and 'crude argon' (which included all the residual gases after the removal of carbon dioxide, oxygen and nitrogen) were analyzed separately by RAKESTRAW and EMMEL (1938). Their results for nitrogen varied from 95 to 108 per cent and for the crude argon from 94 to 124 per cent. They ascribed the larger variation for the latter to less accurate measurements and to the possibility that traces of hydrogen or hydrocarbons were present in the crude argon. HAMM and THOMPSON (1941) found a range, for the combined nitrogen and inert gas content, of 93·7 to 109·1 per cent in surface waters, and of 91 to 102 per cent in Pacific Ocean waters.

Despite the variations described above, nitrogen gas dissolved in sea water is usually assumed to be conservative, i.e., the nitrogen concentration is assumed to be unaltered by biological and chemical activity (SVERDRUP, JOHNSON and FLEMING, 1942, pp. 186, 188; RICHARDS, 1957, p. 102). BUCH based a technique for determining the 'biologisch unbeeinflussten Sauerstoffs' (or, in the nomenclature of this paper, the 'initial oxygen concentration'), and the consumption of oxygen, partly upon the assumption that the combined nitrogen and crude argon content is conservative. In a refinement of BUCH's method, RAKESTRAW and EMMEL assumed nitrogen and crude argon were *each* biologically and chemically inert.

*As used here, the word 'aerobic' is a misnomer. (See the authors' note in the following paper by RICHARDS and BENSON (1961)). We propose that in the future the word 'oxic' be used to convey the idea intended here, i.e., that the water contains dissolved oxygen.

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**The percentage saturation of a particular dissolved gas is defined to be the ratio of the concentration of the gas to the solubility of that gas in water of the observed *in situ* temperature and salinity, which is in equilibrium with a normal atmosphere at a pressure of 760 mm of mercury. As used, the pressure refers sometimes to 760 mm of mercury exclusive of the partial pressure of water vapour ('dry' atmosphere), and sometimes to a total pressure of 760 mm of mercury including that of water vapour ('wet' atmosphere).

††The term 'atmospheric nitrogen' is avoided because in this paper it will be used in its literal sense to mean nitrogen gas in or from the atmosphere.

If nitrogen is conservative, it is evident that one or more physical effects must be responsible for the observed variations in the percentage saturation of nitrogen. Both BUCH, and RAKESTRAW and EMMEL, assumed that 'the apparent changes in "percentage saturations" are only the result of temperature and salinity variations in the water . . . . ' (RAKESTRAW and EMMEL). The data of RAKESTRAW and EMMEL were re-examined by CARRITT (1954), who pointed out that the majority of the variations in the percentage saturation of nitrogen could have been due to atmospheric pressure fluctuations over the sea surface.*

From the discussion above it is clearly desirable to determine the physical and/or biological causes responsible for the observed variations in the percentage saturation of nitrogen. The approach used in the research reported here was in some respects similar to that of BUCH and RAKESTRAW and EMMEL. The concentration of argon, a gas influenced only by physical effects, was compared with the concentration of nitrogen. The analyses were carried out with a mass spectrometer, instead of by gasometric techniques.

THEORETICAL CONSIDERATIONS

The fact that the percentage saturations of gases dissolved in surface sea water do not differ greatly from 100 per cent suggests that the gases in the atmosphere are approximately in thermodynamic equilibrium with the sea surface, i.e., to a first approximation the concentration of each gas is predictable from its solubility coefficient, its partial pressure in the atmosphere, and Henry's law. Stated more accurately : the atmosphere and the oceans are in an approximately steady state such that essentially equilibrium conditions exist at the interface between them, even though within the bodies of the atmosphere and the oceans the conditions are very far from equilibrium. This situation results from the relative kinetics of surface exchange mechanisms and body mixing mechanisms, coupled with the vastly different distances over which they must act. The point is illustrated by noting that the converse situation usually exists in laboratory experiments on the solubilities of gases, where it is much easier to keep the liquid uniformly mixed than it is to ensure that equilibrium is achieved between the liquid and gas phases.

Two questions arise from the above: (1) How closely do conditions at the sea–air interface correspond to equilibrium ? (2) If deviations from equilibrium exist, how can they be utilized to deduce information about the exchange processes ? The first of these, and the question of whether free dissolved nitrogen is conserved within the body of the oceans, are the primary subjects of this paper. As will be seen, some qualitative comments on question (2) can be made, but at the time these experiments were performed, the analytical precision and, particularly, the sampling techniques, were not reliable enough to draw quantitative conclusions. The method of approach will be to propose a theoretical model which assumes both surface equilibrium and conservation of dissolved nitrogen and which can be tested.

Before proceeding to the model it is useful to list the physical factors which may, and presumably do, influence the concentrations of gases dissolved in sea water. They may be separated into two categories :

*CARRITT (private communication) has discovered that some of his numbers were incorrect, but his main thesis is not invalidated.

A. Surface factors :
1. Water temperature.
2. Salinity.
3. Atmospheric pressure.
4. Atmospheric humidity.
5. Air temperature.
6. Surface conditions.
7. Kinetics of near-surface mechanisms.

B. Body factors :
1. Radioactive decay.
2. Influx (or efflux) through the sea floor.
3. Mixing.
4. Radiative heating or heating from below. (Although this would not alter the concentration, it would affect the number obtained for the percentage saturation or for any other quantity deduced from the measured temperature).
5. Hydrostatic pressure.

To introduce the model, suppose that in a ' thought experiment ' an element of water at the surface and the element of atmosphere immediately above it, were isolated and found to be in thermodynamic equilibrium. This would mean that the water and air temperatures were identical, that the relative humidity was 100 per cent, and that the concentration of each gas dissolved in the liquid was given by

$$C_i = S' \frac{P_a - P_w}{760} \tag{1}$$

where the symbols have the following meanings :

C_i = initial concentration of the gas in cm^3 per litre (' initial concentration ' in the sense that later we shall assume the element of water sinks and becomes isolated from the atmosphere).

S' = the solubility of the gas, i.e., the number of cm^3 of dissolved gas per litre when the liquid is in equilibrium with a ' normal ' atmosphere whose total pressure, excluding water vapour, is 760 mm of mercury. This is the ' dry ' solubility, like that discussed by Fox (1909) or Benson and Parker (1961). For all surface phenomena we may consider S' to be a function of temperature and salinity only [Klots (1961)].

P_a = atmospheric pressure.

P_w = saturated vapour pressure of water at the temperature and salinity of the water.

It is obvious that the hypothetical situation just described idealizes the real ones in several respects. The relative humidity cannot be 100 per cent – at least on the average – for otherwise evaporation from the sea surface could not occur.* On the other hand, it is quite certain that the relative humidity cannot be zero near the

*It should be noted, however, that the relative humidity at the interface need be only infinitesimally less than 100 per cent to permit evaporation, with air currents continually supplying slightly less saturated air to the surface.

sea surface. If the water and air were not in true thermodynamic equilibrium but in a kind of quasi-equilibrium, i.e., an equilibrium with respect to dissolved gas but not water vapour, equation (1) would take the form :

$$C_i = S' \frac{P_a - RH(P_w)}{760}, \tag{1a}$$

where RH is the relative humidity in the layer of air at the interface. Equations (1) or (1a) implicitly express, in analytical form, CARRITT's (1954) suggested explanation for the variation of percentage saturation in terms of atmospheric pressure, but they go further in that they clarify the role of relative humidity. Because it is impossible to know either the P_a or the RH appropriate to a sample taken from depth, it is evident that the concept of percentage saturation offers only a gross kind of parameter for any gas.

It is difficult to assess the effect on C_i due to a difference in temperature between the air and the water. One might guess that an air temperature greater than the water temperature would cause C_i to be greater than predicted by equations (1) or (1a), with low molecular weight gases affected more than heavier ones. The effect should be small, however, compared to those to be discussed next, and it will be neglected.

Surface conditions and the kinetics of the various mechanisms near the surface probably play significant, interrelated and complicated roles in controlling the dissolved gas concentrations. Two examples will illustrate the problem. At first glance one might expect that the equilibrium situation described above would be most likely to occur with a placid surface across which molecular exchange equilibrium could take place without the complications of surface trapping of air bubbles, etc. Suppose, however, that sub-surface waters were either under- or over-saturated relative to the surface. If internal mixing or molecular diffusion, or both, were more rapid than molecular exchange through the interface, the surface might never have sufficient time to achieve equilibrium. In this case bubbles of air within the liquid, and the bursting of bubbles at the surface (BLANCHARD and WOODCOCK, 1957), might aid in achieving equilibrium through the provision of greater effective surface area.

On the other hand, turbulent surface conditions, especially during violent storms, can cause very extensive trapping of air bubbles which penetrate to depths of many metres (J. KANWISHER, private communication). The solution, partial or complete, of these bubbles would tend to supersaturate the water.

The latter would be accompanied by a most interesting two-sided phenomenon. Consider an air bubble which has been trapped and carried a few metres below the surface. As it descends the partial pressure of each of the gases within the bubble will increase and the gases will tend to go into solution. Assuming that the kinetics of solution of the various gases are not too different, argon and oxygen will be preferentially dissolved relative to nitrogen because the solubility coefficient of the latter is only approximately one-half that of the other two. [The situation is like that in the closed system absorptiometric method of studying gas solubilities. It was FOX (1909) who first recognized the problem arising from the differing solubility coefficients of nitrogen and argon]. Consequently, if one could sample the water alone, without the undissolved bubbles, one would expect to find a greater excess of oxygen and argon than of nitrogen. But if the sampling captured both water and undissolved bubbles

– and this normally would be the case – just the opposite would be observed, because the ratio of nitrogen to argon in the atmosphere is about 83 to 1, whereas the ratio of their solubilities is approximately 39 to 1.

Despite the several possible difficulties with the surface equilibrium model, let us tentatively adopt it and examine its consequences when applied to surface waters in general, and especially those which are ' sources ' for deep water. When the surface water sinks and becomes isolated from the atmosphere, the initial concentrations of nitrogen and argon will each be given by equations of the form of either equation (1) or equation (1a). For our purposes, we shall write down only the expression for the initial *ratio* of the concentrations of the two gases :

$$\frac{N_{2_i}}{A_i} = \frac{N_2'}{A'}, \tag{2}$$

where the symbols have obvious meanings from equation (1). It is evident that atmospheric pressure and relative humidity cancel out, so that variations in either are unimportant. Equation (2) states that if the surface equilibrium model is correct, the initial percentage saturations of the two gases will be equal.

In considering effects within the body of the oceans we shall not assume initially that nitrogen is biologically and chemically inert. In this way the arguments developed will apply to more general situations, for example, to oxygen/argon analyses. The only assumption which will be added to the surface equilibrium model is that the argon concentration remains unchanged during the history of an element of water after it leaves the surface. Stated analytically :

$$A = A_i \tag{3}$$

Where A is the *in situ* concentration of argon at the time of sampling.

Equations (2) and (3) can be combined and manipulated to yield several fruitful formulations :

$$N_{2_i} = \frac{N_2'}{A'} A \tag{4a}$$

$$N_{2_i} = \left(\frac{N_2'}{A'}\right) \left(\frac{A}{N_2}\right) N_2 \tag{4b}$$

$$\frac{N_2}{N_{2_i}} = \left(\frac{N_2}{A}\right) \left(\frac{A'}{N_2'}\right) \tag{5}$$

$$\Delta N_2 = N_2 - N_{2_i} = \left[\frac{N_2}{A} - \frac{N_2'}{A'}\right] A \tag{6}$$

In each case N_2/A is the measured ratio of nitrogen to argon in the gas extracted from a sample of water. The values for N_2'/A' are obtained from measurements of the *in situ* temperature and salinity of the water sample and from laboratory measurements of N_2'/A' vs. temperature and salinity [BENSON and PARKER (1961)].

Equation 4(a) states that the initial concentration of nitrogen may be calculated from the measurement of the *in situ* temperature and salinity of the water sample and the concentration of argon in the sample. If it were more convenient to determine the concentration of nitrogen in the sample, equation (4b) would be more useful, but would necessitate the measurement of N_2/A. If the only quantity desired is the

percentage of the initial nitrogen remaining, i.e., N_2/N_{2_i}, equation (5) states that it is unnecessary to determine anything other than the temperature, salinity and the nitrogen/argon ratio in the gas extracted from the sample.

From equation (6) one can calculate the increase in the concentration of nitrogen which has occurred during the history of the sample of water. It is interesting to compare the decrease in nitrogen concentration, $-\Delta N_2 = N_{2_i} - N_2$, given by equation (6), with what, by analogy with oxygen, would be called the 'apparent nitrogen utilization,' A.N.U. $= N_2' - N_2$.

If the assumption is made that nitrogen is conserved within the body of the oceans, i.e., $N_2 = N_{2_i}$, any one of the equations predicts that

$$\frac{N_2}{A} \bigg/ \frac{N_2'}{A'} = 1 \quad (\text{or } 100\%). \tag{7}$$

Alternatively, a plot of N_2/A vs. N_2'/A' should yield a straight line with a slope of unity. The data from this research will be presented in these forms, but before turning to the experimental results, we shall discuss briefly the physical body factors listed earlier, which might cause changes, either real or apparent, in the nitrogen and argon concentrations.

Radioactivity and influx through the sea floor could affect the argon concentration. One possibility for the genesis of argon 40 (the most abundant isotope) in the atmosphere is that it has been released to the atmosphere from the geosphere and hydrosphere through the radioactive decay of potassium 40. (See, for example, Damon and Kulp, 1958). Calculation shows, however, that for any conceivable turn-over time for the oceans, the increase in the argon concentration should have been undetectable in these experiments.

If two volumes of sea water, individually equilibrated with the atmosphere at two different temperatures, are mixed together, it is well-known that the resulting concentrations of the dissolved gases will be greater than the concentrations obtained by equilibrating the water with the atmosphere at the temperature of the mixture. For example, using the Fox plus Benson and Parker data for nitrogen and argon (Benson and Parker 1961), and taking the extreme case of mixing equal volumes of water at 0 °C and 30 °C (salinities equal 36·13 ‰), the concentrations of nitrogen and argon in the mixture will be 11·51 cm³/litre and 0·3025 cm³/litre, respectively, compared to the corresponding values 10·78 and 0·282 for water equilibrated at the 15 °C temperature of the mixture. For two equal samples at 10 °C and 20 °C, the mixture will contain 10·85 cm³/litre of nitrogen and 0·284 cm³/litre of argon, compared to the 10·78 and 0·282 for 15 °C as above.

A similar effect would result from heating. Water in equilibrium with the atmosphere at 0 °C would contain 14·04 cm³/litre of nitrogen and 0·375 cm³/litre of argon. If, while isolated from the atmosphere, it were heated to 5 °C the actual concentrations would remain unchanged, but the corresponding concentrations deduced from the new temperature would be 12·65 and 0·335.

It is clear that mixing and heating could have significant effects on the concentrations relative to the values deduced from the temperature and salinity. It was these effects which Buch and Rakestraw and Emmel took to be the primary causes of the observed variations in percentage saturation of the gases.

The *ratios* of the concentrations of nitrogen to argon, unlike the concentrations *per se*, are affected very little by either mixing or heating. For the case of mixing two samples at 10 °C and 20 °C the ratio in the mixture is 38·20 compared to the value 38·26 deduced from the temperature. The difference is only 0·16 per cent. In the heating example, the actual ratio would be 37·48, whereas the number obtained from the temperature would be 37·74, a difference of 0·7 per cent. It should be noted that in both cases the tendency is to make the measured ratio, N_2/A, smaller than N_2'/A'.

KLOTS (1961) has pointed out that the increased hydrostatic pressure to which an element of water is subjected when it sinks from the surface to depth, causes the water to become thermodynamically supersaturated, i.e., the solubility coefficient decreases with increased hydrostatic pressure. Although the hydrostatic pressure prevents bubble formation, there will be a tendency for molecular diffusion of the dissolved gases to take place toward regions of lower supersaturation, that is, upward. Because it depends upon molecular diffusion the effect of this factor on the N_2/A ratio is probably negligible compared to even the small effects of mixing and heating, but it should be borne in mind.

EXPERIMENTAL PROCEDURES

Samples were taken during the 1956–57 cruise V12 of the R.V. *Vema* of the Lamont Geological Observatory of Columbia University, and during the August, 1957 cruise of the R.V. *Atlantis* of the Woods Hole Oceanographic Institution.

Nansen bottles were employed as in standard hydrographic work. As soon as possible after the Nansen bottles reached the surface, portions of their contents were transferred to 400 cm^3 glass water sample bottles (Fig. 1). The essential features of the bottle were that once filled, with the double 'O-ring' piston in place and with the stopcock closed, the water was completely isolated from the air, with provision for expansion without excessive danger of breaking the bottle. The pistons were nickel-plated brass. The idea of developing a piston-cylinder type of bottle was suggested by Professor MAURICE EWING. The final design was due to Professor ARNOLD B. ARONS and the first author. The procedure for transferring water to the glass bottles consisted of the following steps :

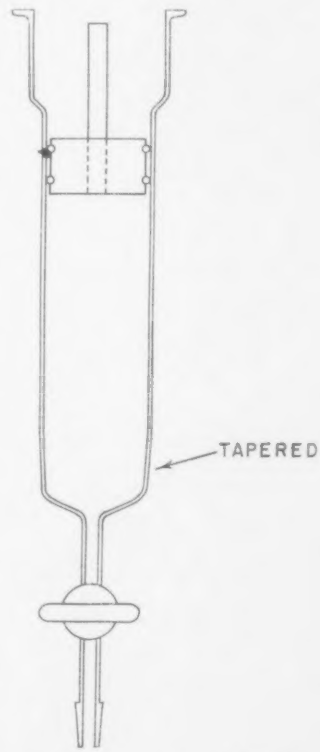

FIG. 1. Glass water sample bottle with 'O-ring' nickel-plated brass piston. Pressure-type stopcock has 6 mm bore. Main cylinder is made of 60 mm heavy wall glass approximately 175 mm long.

1. One end of a tube was attached to the Nansen bottle petcock and the other end inserted through the large end of the glass bottle to a point close to the stopcock at the bottom.

2. With the stopcock closed, water was flowed gently into the glass bottle, displacing air until the water surface rose to approximately the center of the largest tubing. If the bottle had been carefully cleaned, no difficulty was encountered with trapping air at the glass walls. Only the initial water and the water surface came into direct contact with the air, and this water was discarded as described below.
3. The bottle was tipped to an appropriate angle and the piston inserted with a turning motion to prevent trapping of air bubbles near the first 'O-ring.'
4. With the first 'O-ring' fully immersed the piston was pushed in until a seal was made with the main glass cylinder. Then the bottle was inverted, draining the excess water at the top, the stopcock opened, and the piston pushed in to the position shown.

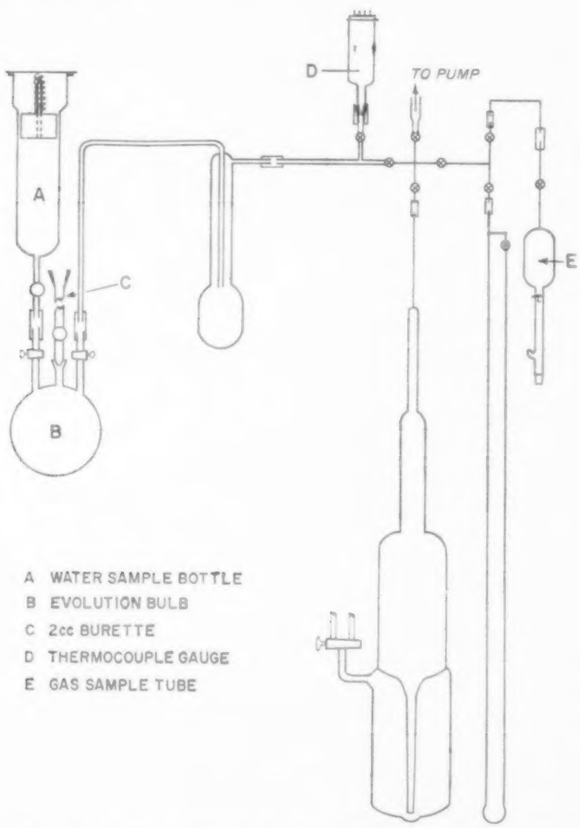

FIG. 2. Toepler pump vacuum manifold for extraction at sea of gases dissolved in water.

5. After closing the stopcock, a spring and clamp assembly was attached to the flange at the top of the bottle to allow small controlled movement of the piston as a presssure release.
6. The samples were stored in a cold dark place until extraction of the dissolved gases, which usually took place within twenty-four hours.

To extract the gases a bottle was attached to a vacuum manifold similar to the one shown in Fig. 2.* The system was made of heavy wall glass except for the thermocouple gauge and the valve manifold above the Toepler pump. The valves were 'Monel' high vacuum 'Sylphon' bellows valves made by 'Hoke.' Extra heavy rubber vacuum tubing was used at several points not only for connecting metal to glass, but also to absorb shock. The unit was attached to a heavily-braced frame mounted on a shock-mounted table.

The system up to the stopcock on the water sample bottle was evacuated by means of a ballast type mechanical pump designed to handle water vapour, to a pressure less than 100 microns (limited primarily by residual water vapour). After closing the pump and thermocouple valves the water was drawn into the evolution bulb. The vacuum tight piston descended slowly during this process and came to rest in a tight seal against the tapered lower portion of the water bottle.

The burette permitted the insertion of approximately 2 cm^3 of concentrated hydrochloric acid to release the dissolved bicarbonate as carbon dioxide. The salt-ice trap served to condense most of the water evaporated while the gas was being Toepler-pumped into the 'break-seal' gas sample tubes. The tubes had been evacuated and outgassed before they were put on shipboard, to reduce the time required to evacuate the system at sea. Four to six Toepler-pumping cycles extracted essentially all of the dissolved gases as indicated by no further change in the manometer. Laboratory tests had shown that, even without the hydrochloric acid, at least 97 to 99 per cent of the gas was evolved, and the addition of the acid made the evolution process even more efficient. In any case, for ratio determinations the errors introduced by imperfect extraction were probably not significant. The gas sample tubes were sealed with a glass-blowing torch and stored in crates until the end of the cruise.

At Amherst the gas samples were further processed to eliminate all water vapour and to separate vapours like carbon dioxide, which are condensable in liquid air, from the nitrogen, oxygen and argon. For reasons explained by Benson and Parker (1961), the oxygen was then removed by cycling the gas through a 'Vycor' furnace filled with copper turnings at 700 °C, followed by a liquid air trap. The procedure for carrying out the N_2/A analyses with the mass spectrometer were identical with those described by Benson and Parker.

In addition to the determination of the ratio of nitrogen to argon in each sample, measurements were made on the *Atlantis* samples of the ratio of the abundances of the two stable nitrogen isotopes with masses 14 and 15, relative to their ratio in atmospheric nitrogen. Precision 'double collection' techniques (McKinney, *et al.* 1950) were employed for this purpose.

DATA AND RESULTS

The data from 74 samples taken at stations in the North Atlantic Ocean and the South Atlantic Ocean are shown in Table 1. The hydrographic data were supplied by the Lamont Geological Observatory and the Woods Hole Oceanographic Institution. Salinities given to only three significant figures were taken from Wüst profiles and are approximate. Because the N_2'/A' ratio is almost independent of salinity, values for the latter are given only to indicate that they were in the range of 33 to

*The manifold shown was employed on the *Atlantis*. A more complicated manifold, which was a modification of one reported by Rakestraw and Emmel (1937), was used on the *Vema*.

Table 1. Nitrogen/argon and nitrogen isotope data from Vema *V12 cruise and R.V.* Atlantis *stations 5590 and 5594*

	Sample	Date	Latitude	Longitude	Sonic Depth (m)	Sample Depth (m)	Salinity (‰)	Potential Temperature (°C)	$\frac{N_2}{A}$	$\frac{N_2'}{A'}$	$\frac{N_2}{N_{2i}}$ (%)	$\delta_{29/28}$ (‰)
	V-12											
Faukland Current	3	7-3-57	41° 44·5′ S	60° 59′ W	ca 59	0	34·566	13·61	38·46	38·19	100·7	
Faukland Current	6	14-3-57	41° 02·5′ S	60° 48·5′ W	59	55	33·391	13·08	38·04	38·16	99·7	
Faukland Current	8	16-3-57	45° 43′ S	66° 20′ W	91	82	33·297	7·61	37·62	37·88	99·3	
Faukland Current	7	16-3-57	45° 34′ S	65° 50′ W	95	91	33·237	8·15	37·96	37·91	100·1	
	9	3-4-57	41° 12·3′ S	51° 18′ W	5545	0	34·688	16·60	38·29	38·35	99·8	
	10	7-4-57	38° 55·5′ S	40° 04′ W	5092	1065	34·356	2·78	37·28	37·63	99·1	
South of Walvis Ridge	12	17-4-57	39° 21·2′ S	01° 08·5′ E	5101	45	34·672	13·90	37·94	38·20	99·3	
South of Walvis Ridge	13	18-4-57	36° 56·5′ S	04° 39′ E	5101	0	—	15·10	38·69	38·27	101·1	
South of Walvis Ridge	14	,,	,,	,,	5101	ca 2900	34·860	1·88	37·44	37·57	99·6	
South of Walvis Ridge	16	,,	,,	,,	5101	ca 3800	35·5	? 2·83	37·76	37·63	100·3	
South of Walvis Ridge	15	,,	,,	,,	5101	ca 4800	? 35·487	? 0·96	38·27	37·53	102·0	
South of Walvis Ridge	17	19-4-57	34° 42′ S	06° 30′ E	5298	ca 1200	? 34·802	2·83	37·97	37·63	100·9	
South of Walvis Ridge	19	,,	,,	,,	5298	ca 2377	34·8	(2·42)	37·47	37·60	99·6	
South of Walvis Ridge	20	,,	,,	,,	5298	ca 4300	34·8	0·75	37·48	37·52	99·9	
South of Walvis Ridge	18	,,	,,	,,	5298	ca 4500	34·7	0·77	37·41	37·52	99·7	
	*22	29-4-57	32° 13′ S	16° 15·5′ E	448	0	35·1	20·11	38·51	38·53	99·9	
	21	,,	,,	,,	448	137	35·0	10·96	37·95	38·05	99·7	
	23	30-4-57	30° 14·9′ S	13° 03′ E	3063	988	34·4	3·02	37·57	37·64	99·8	
	24	,,	,,	,,	3063	1966	34·9	2·81	37·53	37·63	99·7	
	25	,,	,,	,,	3063	2980	34·9	2·28	37·09	37·60	98·6	
Benguela Current	28	4-5-57	24° 17′ S	14° 07·5′ E	130	0	35·3	14·17	38·63	38·22	101·1	
Benguela Current	29	,,	,,	,,	130	? 64	35·5	11·89	38·28	38·10	100·5	
Benguela Current	30	5-5-57	22° 31·5′ S	14° 14·5′ E	75	0	35·2	12·7	38·34	38·15	100·5	
Benguela Current	31	,,	,,	,,	75	64	35·2	12·06	38·53	38·11	101·1	
	**34	6-5-57	22° 53′ S	10° 17·5′ E	—	0	—	20·44	38·49	38·55	99·8	
	**35	,,	,,	,,	—	0	—	20·44	38·63	38·55	100·2	
	**36	,,	,,	,,	—	0	—	20·44	38·46	38·55	99·8	
	38	8-5-57	22° 56′ S	04° 50′ E	2740	? 54	35·6	21·07	39·11	38·58	101·4	
	40	,,	,,	,,	2740	? 265	35·0	ca 12·56	37·75	38·14	99·0	
	41	,,	22° 41′ S	03° 16′ E	5030	493	34·5	7·01	37·71	37·85	99·6	
	42	,,	,,	,,	5030	988	34·5	3·69	37·50	37·68	99·5	
	43	,,	,,	,,	5030	1500	34·8	3·46	37·15	37·66	98·6	
	44	,,	,,	,,	5030	2012	34·9	2·88	37·47	37·63	99·6	
	45	,,	,,	,,	5030	3144	34·9	2·31	37·88	37·60	100·7	
	46	,,	,,	,,	5030	4150	34·9	2·07	37·09	37·58	98·7	
	48	12-5-57	15° 16·5′ S	07° 00′ E	5038	4938	34·9	2·14	37·64	37·59	100·1	
	49	20-5-57	5° 54·9′ S	10° 33′ E	2140	0	ca35·8	27·56	39·44	38·92	101·3	
	50	,,	,,	,,	2440	2002	36·0	3·50	37·60	37·66	99·8	

Table 1 (*contd.*)

Sample	*Date*	*Latitude*	*Longitude*	*Sonic Depth* (m)	*Sample Depth* (m)	*Salinity* (‰)	*Potential Temperature* (°C)	$\frac{N_2}{A}$	$\frac{N_2'}{A'}$	$\frac{N_2}{N_{2i}}$	$\delta_{29/28}$ (‰)
V-12											
54	26-5-57	04° 49·0′ S	02° 37·5′ E	5500	256	35·6	11·55	37·99	38·08	99·8	
51	,,	,,	,,	5500	2950	36·3	2·51	37·55	37·61	99·8	
52	,,	,,	,,	5500	3930	34·9	2·10	37·61	37·59	100·0	
56	27-5-57	04° 23·9′ S	00° 14′ W	4755	475	34·7	7·96	38·03	37·90	100·3	
57	,,	,,	,,	4755	1024	34·6	4·16	37·83	37·70	100·3	
58	,,	,,	,,	4755	2012	34·9	3·31	37·36	37·66	99·2	
59	,,	,,	,,	4755	? 4572	34·9	2·00	36·62	37·58	97·4	
60	1-6-57	01° 52′ N	16° 04·5′ W	4800	ca 3600	34·72	1·96	37·68	37·58	100·3	
61	2-6-57	00° 18·5′ N	18° 49′ W	—	0	—	25·22	38·79	38·79	100·0	
*62	5-6-57	32° 13′ S	16° 15·5′ E	448	0	35·1	20·11	38·70	38·53	100·4	
A-5590											
13	13-8-57	32° 04′ N	61° 02′ W	4645	1	36·30	26·64	39·20	38·87	100·8	+ 0·24
14	,,	,,	,,	,,	49	36·41	23·26	39·27	38·69	101·5	0·17
15	,,	,,	,,	,,	98	36·59	20·52	38·86	38·55	100·8	0·25
16	,,	,,	,,	,,	584	36·33	16·87	—	38·36	—	—
17	,,	,,	,,	,,	779	35·80	13·19	38·22	38·17	100·1	0·15
18	,,	,,	,,	,,	877	35·34	10·70	38·07	38·04	100·1	0·23
19	,,	,,	,,	,,	975	35·26	8·64	37·96	37·93	100·1	0·19
20	,,	,,	,,	,,	1243	35·14	5·40	38·57*	37·76	—	0·04
21	,,	,,	,,	,,	1757	35·08	3·92	38·85*	37·69	—	0·18
22	,,	,,	,,	,,	2823	35·00	2·84	37·57	37·63	99·8	0·46
23	,,	,,	,,	,,	3552	34·87	2·20	37·50	37·59	99·8	0·04
24	,,	,,	,,	,,	3925	34·96	? 2·05	36·69	37·58	97·6	0·19
25	,,	,,	,,	,,	4396	34·84	? 1·89	36·93	37·57	98·3	0·07
A-5594											
64	18-8-57	31° 55′ N	42° 20′ W	3813 to 3840	1	36·21	26·47	38·79	38·86	99·8	− 0·06
75	,,	,,	,,	,,	43	—	—	—	—	—	+ 0·07
65	,,	,,	,,	,,	87	36·59	19·39	38·37	38·49	99·7	− 0·06
66	,,	,,	,,	,,	430	36·00	15·24	38·11	38·28	99·6	− 0·16
67	,,	,,	,,	,,	523	35·89	14·61	37·89	38·24	99·1	+ 0·05
68	,,	,,	,,	,,	617	35·69	13·61	37·94	38·19	99·3	0·11
69	,,	,,	,,	,,	942	35·26	7·82	37·63	37·89	99·3	0·19
70	,,	,,	,,	,,	1644	34·96	4·17	37·20	37·70	98·7	0·05
71	,,	,,	,,	,,	2186	34·98	3·37	37·26	37·66	98·9	0·10
72	,,	,,	,,	,,	2737	34·98	2·84	37·24	37·63	99·0	0·12
76	,,	,,	,,	,,	3104	34·91	2·54	—	37·61	—	0·31
73	,,	,,	,,	,,	3471	34·88	2·34	—	37·60	—	0·25
74	,,	,,	,,	,,	3838	34·93	2·15	—	37·59	—	0·14

36 per mille for which the BENSON and PARKER N_2'/A' values are valid. Dissolved oxygen was present in all samples.

Samples V12–22 and V12–62 were identical samples taken at the same time. Sample V12–22 was processed immediately, and sample V12–62 was deliberately stored in the dark for approximately five weeks before extraction of the dissolved gases. Samples V12–34, 35 and 36 were identical. The first was processed immediately, whereas the second was stored in the dark for seven hours and the third in sunlight for seven hours before extractions of the gases.

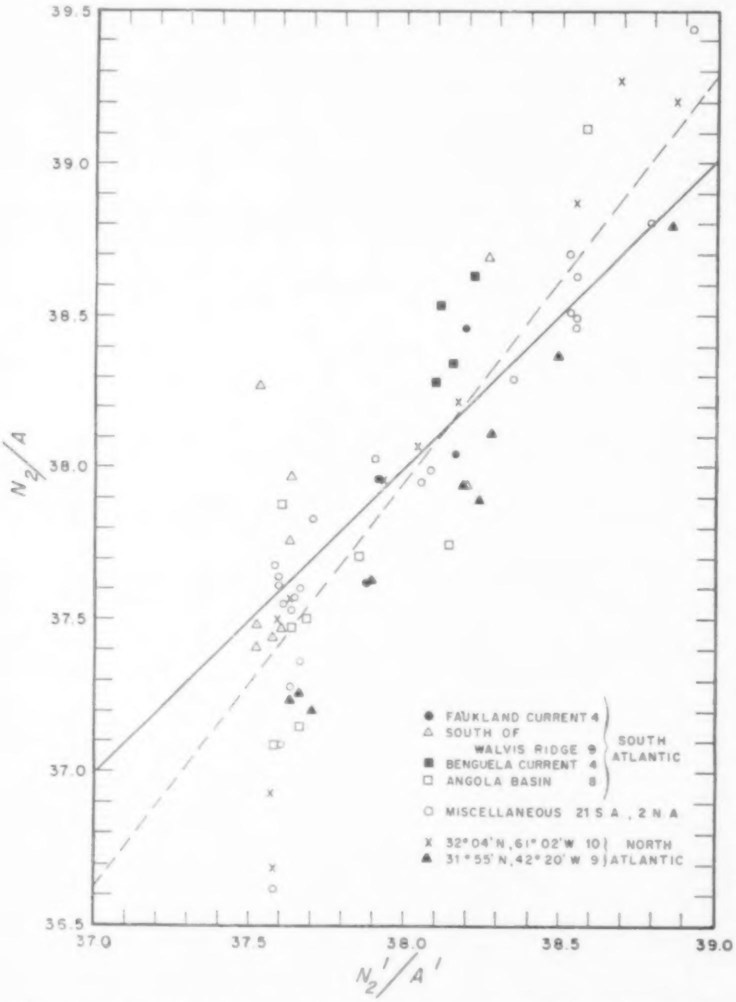

FIG. 3. Expanded graph of N_2/A vs. N_2'/A' for all data. Dashed line is linear least squares fit of all data. Solid line represents $N_2/A = N_2'/A'$.

Sample A5590–16 was lost. The values of N_2/A for samples A5590–20 and 21 were in error because of contamination through a crack in one of the sample system manifolds on the mass spectrometer. Fortunately, the isotope ratio measurements

had already been made before the contamination. Samples A5594–73 to 76 were not analyzed for N_2/A because of a major break in one of the manifolds on the mass spectrometer. The measurements had to be terminated before the break could be repaired and high vacuum again achieved.

It is clear from the earlier discussion that it is most appropriate to use the potential temperature for determination of the values of N_2'/A' from the table given by BENSON and PARKER. Accordingly, the measured temperatures were converted to potential temperatures, although the precision of the measurements was not high enough to necessitate it.

The corresponding values for N_2/A and N_2'/A' were used to calculate N_2/N_{2_i} from equation (5). The results are given in per cent in the second-to-last column in Table 1. Of the 67 values for N_2/N_{2_i}, 38 (or 57 per cent) lie within the range 100 $\pm$ 0·5 per cent, 52 (or 78 per cent) within 100 $\pm$ 1·0 per cent, and all but two values within 100 $\pm$ 2·0 per cent. The standard deviation of all values from 100 per cent is 0·86 per cent, and if samples V12–15, V12–59 and A5590–24 are disregarded, the standard deviation is 0·71 per cent. The average of all values is 99·84 per cent.

The estimated precision of the mass spectrometer measurements alone, as determined from the standard deviation of repeated measurements, was approximately 0·2 per cent. In addition, errors of unknown magnitude were certainly possible in the techniques used for sampling the water and processing to remove the gases. Any possible systematic error in the values of N_2'/A', associated with the calibration of the spectrometer (BENSON and PARKER, 1961), would have caused no error in the present work. Because the same calibration was used, the solubility samples and the ocean samples were effectively compared directly with one another. Small random or systematic errors from other sources in the N_2'/A' vs. temperature measurements cannot be ruled out.

After a consideration of the possible errors involved, we believe that within $\pm$ 1 per cent, and perhaps more closely, the experimental results in the present work verify the applicability* of the surface equilibrium model, and show that nitrogen is biologically and chemically inert in the waters studied. The N_2/A results are also represented in the highly expanded graph of Fig. 3, where values for N_2/A are plotted against the corresponding values for N_2'/A'. The solid line is the straight line to be expected if $N_2/A = N_2'/A'$. The dashed line is a linear least squares fit for all the experimental points. At $N_2'/A' = 37{\cdot}50$, which corresponds to 0·5 °C, the two curves differ only by 0·53 per cent, and at $N_2'/A' = 38{\cdot}89$, which corresponds to 27 °C, they differ by 0·64 per cent.

Having established in ' gross ' terms the conclusions stated above, we are tempted to interpret the fine detail in the last paragraph. It is quite possible, and perhaps likely, considering the spread in the points at low temperatures, that the difference between the solid and dashed lines is a result simply of small random or systematic errors. Nevertheless, it is interesting to note that the experimental curve lies above the theoretical curve at high temperatures where most surface waters are represented. This is what would be expected if trapping of air bubbles from surface turbulence were significant. Furthermore, at the lower temperatures (deep samples) the difference

*The word ' applicability ' is chosen advisedly, for it has not been proven that the observed variations in the percentage saturation of nitrogen are due to surface effects, but only that the surface equilibrium model is consistent with the N_2/A results.

is in the direction to be expected from mixing or heating. Examination of these possibilities must await more precise techniques.

Fig. 4 contains expanded graphs of the experimental results for N_2/A vs. depth for four stations. The solid line in each case is a plot of N_2'/A' vs. depth. The rather large random deviations in the Angola Basin graph may have been due to sampling or processing difficulties. A similar explanation would seem to apply to the two

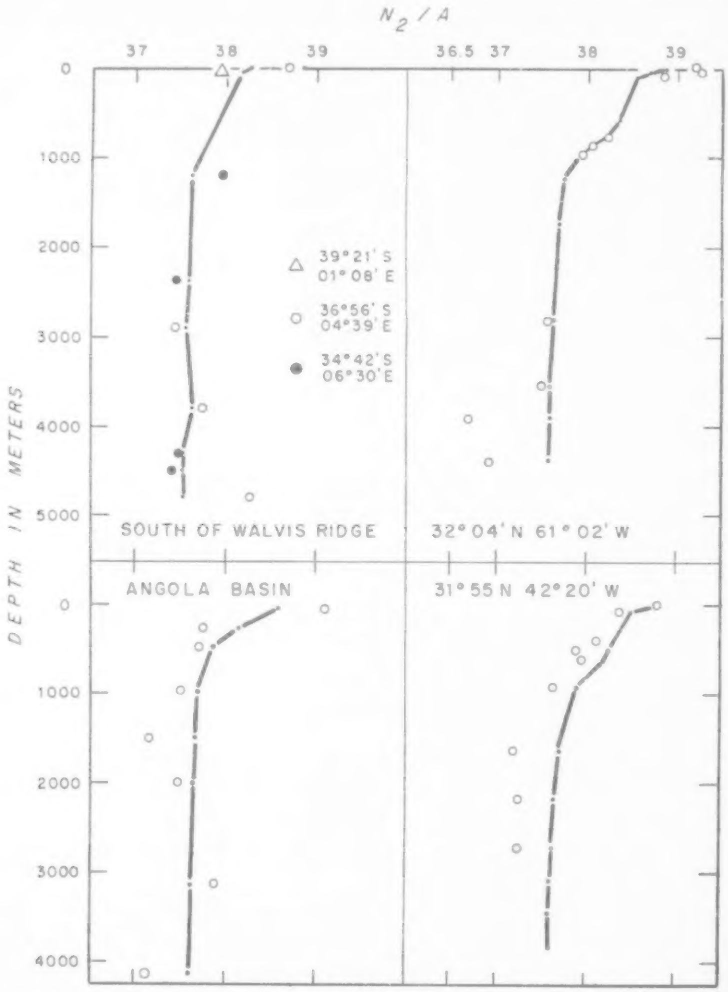

FIG. 4. Expanded graph of data for N_2/A vs. depth for two stations in the North Atlantic and two stations in the South Atlantic. Curves are graphs of N_2'/A' vs. depth.

deepest samples at 32° 04′ N, 61° 02′ W. The smooth pattern of points for 31° 55′ N, 42° 20′ W, suggests that the differences of N_2/A from N_2'/A' may be significant. If they are, the results might be interpreted to mean that a general rise of older, mixed or heated water, was occurring in that region. This, of course, is highly speculative, but further study seems warranted.

The results of the nitrogen isotope determinations on the *Atlantis* samples are presented in the last column of Table 1. The quantity measured with the mass spectrometer was the per mille difference between the ratio of molecular nitrogen 29 to

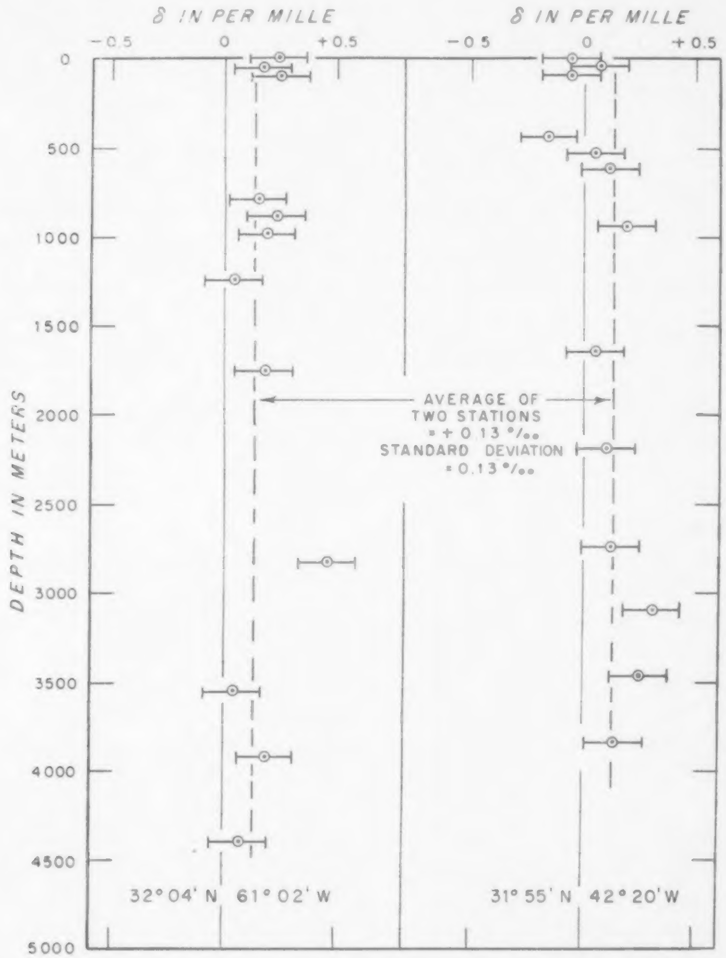

FIG. 5. Graphs of $\delta_{29/28}$ vs. depth for two North Atlantic stations.

molecular nitrogen 28 for each sample, and the corresponding ratio for atmospheric nitrogen.

$$\delta_{29/28} = \frac{\left(\dfrac{^{14}N\,^{15}N}{^{14}N\,^{14}N}\right)_x - \left(\dfrac{^{14}N\,^{15}N}{^{14}N\,^{14}N}\right)_{\text{air}}}{\left(\dfrac{^{14}N\,^{15}N}{^{14}N\,^{14}N}\right)_{\text{air}}} \times 10^3.$$

The values for δ for the two stations are plotted vs. depth in Fig. 5. Because visual examination of the results suggests that the isotope ratio is uniform with depth, a

simple numerical average of all the values has been calculated and found to be +0·13 per mille, with a standard deviation of 0·13 per mille. Although a small correction was necessary for a systematic difference between the two sample systems on the mass spectrometer,* we believe that the difference between the dissolved nitrogen and atmospheric nitrogen may be significant. If it is, the results indicate that the solution of nitrogen in sea water, under conditions at sea, is accomplished by a small fractionation of the isotopes with the dissolved molecular ratio being larger by approximately one part in 10,000.

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Nitrogen/argon and nitrogen isotope ratios in two anaerobic environments, the Cariaco Trench in the Caribbean Sea and Dramsfjord, Norway*

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Abstract—Mass spectrometric measurements of nitrogen/argon and nitrogen isotope ratios have been used to examine the fate of nitrogen arising from the decomposition of organic matter in two anaerobic marine environments, the Cariaco Trench in the Caribbean Sea and the Dramsfjord in Norway.

Values of N_2/A in these waters are larger than would be expected from dissolved atmospheric gases. By assuming that the A concentration is biologically unaffected, the excess quantities of N_2 can be calculated. These are in good agreement with the amounts of nitrogen which would be expected to arise from the decomposition of organic matter. The latter values are computed from the observed concentrations of nitrogen compounds and either the observed concentrations of inorganic phosphate or the amounts of oxygen (either free or bound in the sulphate ion) consumed from the water.

It is shown that nitrogen isotope ratios are markedly different in the nitrogen of biogenic origin from those in nitrogen dissolved from the atmosphere.

It is shown that it is probable that free nitrogen can be formed from organic matter only through the denitrification of nitrate, formed as an intermediate.

INTRODUCTION

THE statistically constant ratio of phosphorus to nitrogen in sea-water and in marine organisms, N : P = 15 or 16 : 1, by atoms, has been established by REDFIELD (1934, 1942), COOPER (1938), FLEMING (1940) and others. FLEMING also reported the average ratios of carbon to these elements in marine plankton to be C : N : P = 106 : 16 : 1, and REDFIELD (1934) has shown that in sea-water the ratio of the change of carbonate-carbon to nitrogen is C : N = 7 : 1. Upon the ultimate decomposition of organic matter having the above composition, inorganic forms of phosphorus, nitrogen and carbon are released to the water in these same ratios. In aerobic waters this latter process is accompanied by the consumption of free oxygen from the water in, statistically, the ratios AOU : C : N : P = 270 : 106 : 15 : 1 (RICHARDS and VACCARO, 1956), where AOU is the apparent oxygen utilization.

In the oxygen-free waters of the Cariaco Trench, however, RICHARDS and VACCARO found the ratio of oxygen consumption to phosphorus release to be only 235 : 1. This ratio takes into account the oxygen from the sulphate ions which, in the absence of free oxygen, are reduced to sulphides (H_2S, HS^-, $S^=$). Furthermore, under anaerobic conditions, the nitrogen, assumed to be released initially in the amino ($-NH_2$) form, does not appear in the form of nitrate (NO_3^-). In the Cariaco Trench, RICHARDS and VACCARO found that nitrate and nitrite either were absent or were present in

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traces quantitatively unimportant to the discussion to follow. The quantities of ammonia-nitrogen in the anaerobic depths, although larger than found in the open ocean, were too small to account for all the nitrogen which should have been present, as estimated from the above ratios and either the phosphate concentrations or the quantities of oxygen consumed. They suggested that the balance of nitrogen might be present as free, molecular N_2 in solution, amounting to approximately 0·35 ml/l or about 3·5 per cent of the quantity of atmospheric nitrogen in the water.

In order to elucidate further the fate of nitrogen in anaerobic environments, we have carried out studies on the Cariaco Trench, off the north coast of Venezuela, and on the Dramsfjord, an arm of the Oslofjord in Norway.

THEORETICAL CONSIDERATIONS

The amount of free nitrogen expected from biological sources can be computed from the ratios quoted above and either the phosphate concentration or the sum of the dissolved oxygen consumption (AOU) plus four times the sulphide concentration:

$$N_2^{B\,(P)} = 15\,(PO_4^{\equiv}) - (NH_3 + NO_2^- + NO_3^-) \tag{1}$$

$$N_2^{B\,(O)\,\mathrm{aerobic}} = 0{\cdot}056\,(AOU) - (NH_3 + NO_2^- + NO_3^-) \tag{2}$$

$$N_2^{B\,(O)\,\mathrm{anaerobic}} = 0{\cdot}064\,(AOU + 4S^{=}) - (NH_3 + NO_2^- + NO_3^-) \tag{3}$$

The AOU values are expressed in microgramme atoms per litre and can be estimated from the observed concentrations of oxygen and the equilibrium solubilities of oxygen in sea-water at the observed temperatures and salinities, using the nomogram of RICHARDS and CORWIN (1956), constructed from the solubility results of TRUESDALE *et al.* (1955). The symbols $PO_4^{\equiv}$, $S^{=}$, NH_3, NO_2^- and NO_3^- are the concentrations of phosphate-phosphorus, sulphide-sulphur, and ammonia-, nitrite-, and nitrate-nitrogen, respectively, in microgramme atoms per litre.

For reasons discussed in the preceding paper (BENSON and PARKER, 1961a), the uncertainties involved in estimating the concentrations of dissolved atmospheric nitrogen are larger than the small amounts of the hypothesized free biogenic nitrogen. Consequently, absolute gasometric determinations of the concentrations of total dissolved nitrogen would yield no information. On the other hand, the method employed by BENSON and PARKER, using dissolved argon as a reference, is particularly appropriate for this problem. The presence of biogenic nitrogen would alter the nitrogen/argon ratios in the dissolved gases, making the ratios larger than if only atmospheric nitrogen were present.

BENSON and PARKER have shown (on the basis of certain assumptions, which, from their results in aerobic waters, seem to be valid) that the measured nitrogen/argon ratios can be used to compute $\Delta\,N_2$, the amount of nitrogen in excess of that expected from the atmosphere, from the equation

$$\Delta\,N_2 = \left(\frac{N_2}{A} - \frac{N_2'}{A'}\right) A \tag{4}$$

N_2/A is the measured volumetric nitrogen/argon ratio in the dissolved gas from a sample. N_2'/A' is the ratio of the solubilities of nitrogen and argon in water equilibrated with air at the potential temperature and salinity of the sample. BENSON and PARKER (1961a) have reported preliminary determinations of N_2'/A' vs. temperature

and salinity. The absolute concentration of argon dissolved in the sample is denoted by A.

If free biogenic nitrogen is produced, it might be expected to have an isotope ratio, $R_B = {}^{29}N_2{}^B / {}^{28}N_2{}^B$, different from that of the dissolved atmospheric nitrogen (see, for example, HOERING, 1955). Although the proportion of biogenic nitrogen to atmospheric nitrogen in the dissolved gas would be small, its presence might alter the total dissolved nitrogen isotope ratio, R, sufficiently to be detectable with very precise measurements. Furthermore, if biological processes do alter the isotope ratio it is possible to calculate an approximate value for R_B, as follows :

Let R_A and R_S be the isotope ratios in atmospheric nitrogen and in atmospheric nitrogen dissolved in ' normal ' aerobic sea-water. Let δ_S, δ and δ_B be the per mille differences between R_S, R and R_B, respectively, and R_A, *i.e.*,

$$\delta_S \equiv \left(\frac{R_S}{R_A} - 1\right) 10^3, \qquad \delta \equiv \left(\frac{R}{R_A} - 1\right) 10^3, \qquad \delta_B \equiv \left(\frac{R_B}{R_A} - 1\right) 10^3. \tag{5}$$

By definition,

$$R \equiv \frac{{}^{29}N_2{}^S + {}^{29}N_2{}^B}{{}^{28}N_2{}^S + {}^{28}N_2{}^B},$$

or

$${}^{28}N_2{}^S\, R + {}^{28}N_2{}^B\, R = {}^{29}N_2{}^S + \frac{{}^{29}N_2{}^B}{{}^{28}N_2{}^B}\, {}^{28}N_2{}^B.$$

Dividing by ${}^{28}N_2{}^S$, substituting R_S and R_B for their equivalents, and rearranging gives

$$R_B = R + \frac{{}^{28}N_2{}^S}{{}^{28}N_2{}^B}(R - R_S).$$

Upon substituting for R_B, R and R_S from (5) and simplifying :

$$\delta_B = \delta + \frac{{}^{28}N_2{}^S}{{}^{28}N_2{}^B}(\delta - \delta_S).$$

Moreover, to a very good approximation

$$\frac{{}^{28}N_2{}^S}{{}^{28}N_2{}^B} \simeq \frac{N_2{}^S}{\Delta N_2} = \frac{N_2 - \Delta N_2}{\Delta N_2} = \frac{N_2/A - \Delta N_2/A}{\Delta N_2/A} = \frac{N_2'/A'}{N_2/A - N_2'/A'},$$

where equation 4 has been used.

Therefore,
$$\delta_B = \delta + (\delta - \delta_S)\frac{N_2'/A'}{N_2/A - N'_2/A'}. \tag{6}$$

The result is expressed in terms of the δ's rather than the R's since it is δ which is measured with the mass spectrometer.

PROCEDURES, DATA AND RESULTS

Samples were collected in the Dramsfjord on 14 August 1957, and from the Cariaco Trench on 8 and 9 November 1957, for measurements of the dissolved gases. Simultaneous observations of salinity, temperature, dissolved oxygen or sulphide, nitrate, nitrite, ammonia and phosphate were made.

Inorganic phosphates were determined by the method described by WATTENBERG (1937), WOOSTER and RAKESTRAW (1951) and ROBINSON and THOMPSON (1948a). Nitrates were determined by the method of MULLIN and RILEY (1955), ammonia by either the method of RILEY and SINHASENI (1957) or by a modification of ATKINS' (1957) adaptation of the method of KRUSE and MELLON (1953). ROBINSON and THOMPSON (1948b) have described the method used for determining nitrites, and oxygen was determined by the Winkler method. Sulphide analyses were made by a modification of the standard colourimetric method of the American Public Health Association (1946) due to Dr. S. A. el Wardani (private communication).

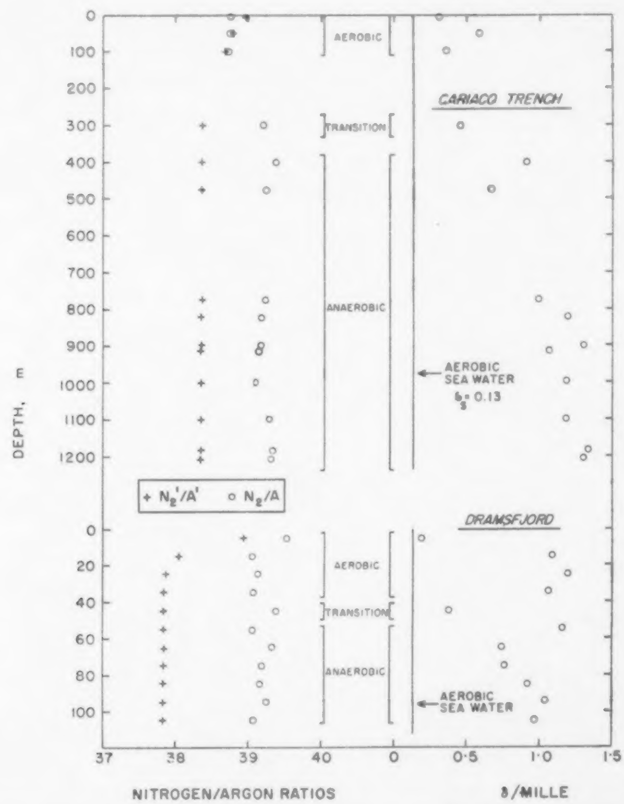

Fig. 1. Vertical distribution of the nitrogen/argon ratios expected from atmospheric gases (N_2'/A') and those observed (N_2/A), and of the values of δ in the Cariaco Trench and Dramsfjord.

BENSON and PARKER (1961a) have described the techniques for obtaining and processing samples of sea-water for dissolved gas analyses, and the mass spectrometric methods used for the N_2/A and $^{29}N_2/^{28}N_2$ ratio measurements. The water samples were stored for several months before the gases were extracted, but we have no reason to believe this had any effect on the dissolved nitrogen or argon in the anaerobic samples. As will be discussed below, it is improbable that biogenic nitrogen can be formed except through the intermediate formation of nitrate, so that any organic

matter present in the samples would not be expected to yield N_2 upon its decomposition during storage.

After extraction from the water, the gas was prepared for analysis by immersing the gas sample tubes in liquid air for several minutes and then introducing the gas phase into a vacuum system. There it was cyclically Toepler-pumped through a Vycor furnace filled with pure copper turnings at 700 °C, and a liquid air trap, until all the oxygen was removed. This procedure eliminated any oxides of nitrogen which might have been present, before the gas was introduced into the furnace manifold. The observed excesses of nitrogen, therefore, did not arise from the reduction of oxides of nitrogen.

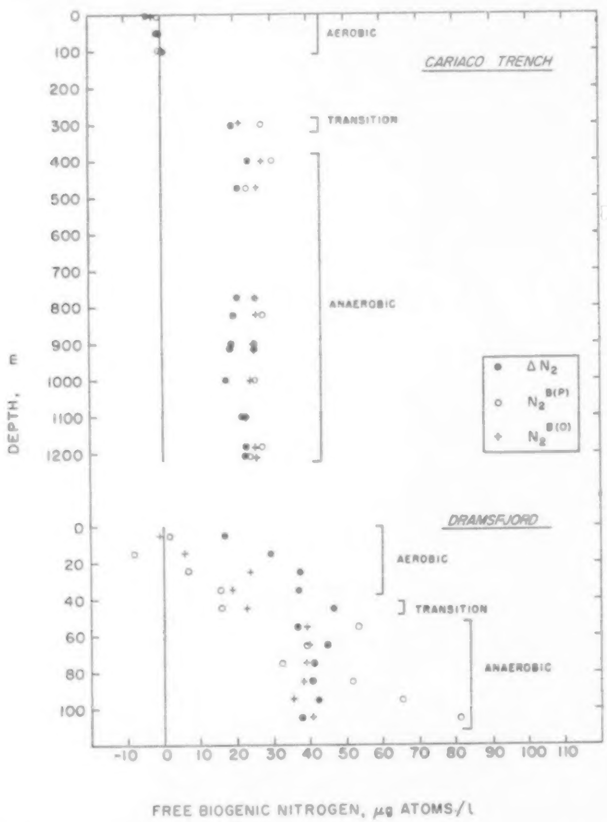

FIG. 2. Vertical distribution of ΔN_2, $N_2^{B(P)}$ and $N_2^{B(0)}$ in the Cariaco Trench and Dramsfjord.

Since the absolute concentration of dissolved argon was not measured, the approximation that A = A′ was used in calculating the values of ΔN_2. The uncertainty of *ca.* ± 5 per cent involved in this approximation (RAKESTRAW and EMMEL, 1938a), corresponded to an uncertainty in ΔN_2 of only about ± 0·01 ml/l for the Cariaco Trench samples and ± 0·02 ml/l for the Dramsfjord samples. The values of A′ given by BENSON and PARKER (1961b), calculated from their N_2'/A' values and the N_2' values of RAKESTRAW and EMMEL (1938b) were used.

Table 1. *Variables in the Cariaco Trench and Dramsfjord*

Depth (m)	T °C	S‰	NO_3^- − N	NO_2^- − N	NH_3 − N	$PO_4^{\equiv}$ − P	AOU	$S^=$ − S	N_2/A (by volume)	δ‰	δ‰	Δ N_2 ml/l	Δ N_2 μga/l	N_2B(P)	N_2B(0)	δ_B‰
Aerobic Zone :								*Cariaco Trench*								
5	28·56	35·90	0·10	± 0	3·0	0·15	9	—	38·76	0·31	—	− 0·045	− 4·0	− 0·8	− 2·6	—
50	25·21	36·53	0·07	0·03	1·8	0·10	22	—	38·74	0·50,	0·65	− 0·011	− 1·0	− 0·4	− 0·7	—
100	23·27	36·70	2·17	0·07	2·1	0·27	88	—	38·73	0·21,	0·51	+ 0·009	0·8	− 0·3	+ 0·6	—
Transition Zone :																
300	16·99	36·22	2·39	0·02	2·8	2·19	471	0·04	39·21	0·46	—	0·219	19·6	27·6	21·2	—
Anaerobic Zone :																
400	16·84	36·20	0·21	0·03	3·6	2·27	471	4·1	39·38	0·91	—	0·267	23·8	30·2	27·3	30·2
476	16·84	36·21	1·37	0·05	5·0	2·00	471	10·4	39·25	0·67	—	0·234	20·9	23·6	26·4	23·9
775	16·88	36·18	0·14	—	9·9	2·38	471	21·6	39·24	0·99	—	0·231	20·6	25·7	25·6	38·5
823	16·76	36·17	± 0	—	10·1	2·50	471	21·9	39·18	1·19	—	0·218	19·5	27·4	25·7	50·2
(900)	16·87	36·18	± 0	± 0	10·5	2·41	471	17·7	39·17	1·30	—	0·213	19·0	25·6	24·6	56·7
915	16·81	36·20	± 0	—	10·6	2·42	471	20·4	39·14	1·06	—	0·208	18·6	25·1	25·7	46·2
(1000)	16·82	36·17	± 0	0·07	11·0	2·38	471	24·0	39·09	1·18	—	0·195	17·4	25·2	24·3	55·6
1101	16·89	36·18	± 0	—	11·3	2·26	471	14·5	39·29	1·18	—	0·245	21·9	22·6	22·6	44·5
1184	16.93	36·17	0·12	0·01	8·5	2·38	471	14·8	39·33	1·22,	1·44	0·255	22·8	27·1	25·3	48·8
1208	16·87	36·17	± 0	0·02	8·4	2·15	471	15·3	39·31	1·30	—	0·252	22·5	23·8	25·6	48·0
Aerobic Zone :								*Dramsfjord*								
5	17·65	± 0	6·4	0·48	0·2	0·60	114	—	39·52	0·19	—	0·188	16·8	1·9	− 0·7	—
15	8·62	24·88	13·0	± 0	± 0	0·33	337	—	39·05	1·08	—	0·332	29·6	− 8·0	5·9	—
25	6·48	29·81	7·2	± 0	0·6	0·97	570	—	39·12	1·20	—	0·420	37·5	6·8	24·1	—
35	5·98	30·23	9·2	± 0	0·2	1·68	511	—	39·07	1·06	—	0·416	37·2	15·8	19·2	—
Transition Zone :																
45	6·02	30·90	8·3	0·19	0·8	1·68	575	—	39·38	0·38	—	0·522	46·6	15·9	22·9	—
Anaerobic Zone :																
55	6·06	30·90	0·4	± 0	4·4	3·90	619	18·0	39·06	1·13,	1·20	0·412	36·7	53·7	39·4	33·1
65	6·00	30·90	± 0	± 0	3·8	2·87	620	16·0	39·32	0·74	—	0·502	44·9	39·2	40·0	16·3
75	5·89	30·90	± 0	± 0	1·2	2·24	621	2·0	39·19	0·79,	0·74	0·462	41·3	32·4	39·1	18·3
85	5·86	30·90	± 0	± 0	1·8	3·57	622	1·0	39·17	0·92	—	0·456	40·7	51·8	38·3	23·2
95	5·84	30·99 (?)	± 0	± 0	5·3	4·73	623	4·0	39·23	1·04	—	0·476	42·5	65·6	35·6	25·6
105	5·83	30·90	± 0	± 0	8·8	6·03	623	38·0	39·08	0·97	—	0·425	38·0	81·6	40·8	26·4

N.B.—Bracketed depths are estimated.
Concentrations, except as indicated, given in microgramme atoms per litre.

In aerobic sea-water, BENSON and PARKER have found a very small, but perhaps significant, difference between R_S and R_A, corresponding to $\delta_S = 0{\cdot}13$‰. This value was used in calculating the values of δ_B in anaerobic waters, but even if the δ_S they found was an artifact arising from a very small systematic error in the isotope ratio measurements, the effect on the calculated values for δ_B would be negligible. (The isotope ratios reported in this paper were measured under identical conditions and concurrently with those reported by BENSON and PARKER, so that if the $\delta_S = 0{\cdot}13$‰ value is too high, our δ values are also high by the same amount. Consequently, the factor $(\delta - \delta_S)$ in the dominant second term in equation 6 would remain unchanged).

The observations of depth, temperature, salinity, chemical variables, nitrogen/argon ratios, and δ values are shown in the first eleven columns of Table 1. As in the Cariaco Trench, the quantities of nitrate and nitrite were negligible in the anaerobic parts of the Dramsfjord. Nitrogen/argon ratios and δ values are plotted against depth in Fig. 1. Values of ΔN_2, $N_2^{B(P)}$, $N_2^{B(0)}$ and δ_B, calculated from the basic data, are entered in the final columns of Table 1. Fig. 2 is a graphical comparison of the values of ΔN_2, $N_2^{B(P)}$ and $N_2^{B(0)}$.

ERRORS

The sources of error in the determination of ΔN_2 have been discussed by BENSON and PARKER (1961a, 1961b). On the basis of their results, we would estimate random errors of approximately $\pm$ 5 and $\pm$ 7 μga/l (or $\pm$ 0·06 and $\pm$ 0·08 ml/l) for the Cariaco Trench and Dramsfjord, respectively. From the uncertainties in the chemical determinations, we estimate random errors in $N_2^{B(P)}$ and $N_2^{B(0)}$ of $\pm$ 2·5 and $\pm$ 1·4 μga/l, respectively, in the anaerobic parts of the Cariaco Trench, and for the corresponding Dramsfjord quantities, $\pm$ 5·6 and $\pm$ 4·8 μga/l. It is evident from the data that, in the anaerobic zones, the variations of ΔN_2, $N_2^{B(P)}$ and $N_2^{B(0)}$ must be considered to be the result of random errors in measurement. The one exception, $N_2^{B(P)}$ in the Dramsfjord, will be discussed below.

Table 2. Summary of the mean values, and standard deviations from the mean, for ΔN_2, $N_2^{B(P)}$, $N_2^{B(0)}$ and δ_B in the anaerobic zones of the Cariaco Trench and the Dramsfjord

	μga/l						‰	
	ΔN_2	*Std. Dev.*	$N_2^{B(P)}$	*Std. Dev.*	$N_2^{B(0)}$	*Std. Dev.*	δ^B	*Std. Dev.*
Cariaco Trench	20·7	1·8	25·6	2·2	25·3	1·3	44	11
Dramsfjord	40·7	3·0	54·0	18·0	38·9	1·8	24	6

Table 2 is a summary of the mean values, and the standard deviations from the means, of ΔN_2, $N_2^{B(P)}$, $N_2^{B(0)}$ and δ_B, in the anaerobic regions of the Cariaco Trench and the Dramsfjord. The standard deviations in ΔN_2 are much smaller than the estimated random errors. This may have resulted from better sampling techniques than those employed in the work of BENSON and PARKER, from the more homogeneous origin of the anaerobic waters, or both.

Any possible systematic error in N_2'/A', associated with the calibration of the mass spectrometer (Benson and Parker, 1961b), would cause no error in the calculated values for ΔN_2, since the same calibration was used in the present measurements. On the other hand, it is estimated that their choice of a linear least squares solution for N_2'/A' vs. temperature might lead to a systematic error in ΔN_2 of up to 4 μga/l in the Cariaco Trench and 6 μga/l in the Dramsfjord, depending upon the temperature. This, together with systematic errors in the AOU values, and in the value for the N : P ratio chosen, could explain the fact that the mean ΔN_2 in the anaerobic Cariaco Trench is slightly smaller than the mean $N_2^{B(P)}$ or $N_2^{B(0)}$, even though the mean values of ΔN_2 and $N_2^{B(0)}$ are essentially equal in the Dramsfjord.

The dominant second term in equation 6 contains the ratio of two small differences, so that even very small errors will affect δ_B considerably. For example, if the mean ΔN_2 for the anaerobic Cariaco samples were increased by 4 μga/l (to be nearly equal to the mean $N_2^{B(0)}$), the mean δ_B would decrease to approximately 37‰.

DISCUSSION

The hypothesis that free molecular nitrogen of biogenic origin is released in anaerobic zones seems to be confirmed by the observations. In the Cariaco Trench, the calculated values of ΔN_2 and N_2^B are in good agreement throughout the water column. The negative values in the aerobic zone, and the differences between the mean values of ΔN_2 and of N_2^B in the anaerobic zone are probably not significant.

In the anaerobic zone of the Dramsfjord, the values of ΔN_2 and $N_2^{B(0)}$ agree very well, but as noted above, the mean value of $N_2^{B(P)}$ is high, with large, statistically significant fluctuations in the individual values. Other observations made in the fjord throughout the preceding year show that the nitrogen to phosphorus ratio there is highly variable and reaches extreme values. It is apparent that neither the nitrogen to phosphorus ratio used (N : P = 15), nor any constant ratio of nitrogen to phosphorus, is applicable in this environment. The fjord receives domestic sewage from the city of Drammen and wastes from wood pulp manufacture (Braarud *et al.* 1958). Under these circumstances, it may be merely fortuitous that the biogenic nitrogen computed from the consumption of oxygen is in agreement with the values of ΔN_2. It is more likely, however, that the C : N ratios in the decomposing organic matter are near the 'normal' 7 : 1 ratio found in plankton organisms, while the phosphate contribution varies independently.

The excesses of free nitrogen, ΔN_2, found in the aerobic zone in the Dramsfjord could be the result of the mixing of aerobic and anaerobic waters. Fig. 3 shows the distribution of oxygen and sulphides at this location (Station bm of Braarud *et al.*, 1958) from November, 1956, until the time of the observations. In the last two months of 1956, a sulphide zone was centred at about 40 m, and extended upward to about 30 m (as determined by Føyn's 1955 oxygen recording device). During the year 1957, the layer was mixed with aerated water, a process which would destroy the sulphides (and perhaps ammonia) by oxidation, but would leave the previously formed free biogenic nitrogen unaffected, except by dilution. Neither Equation (2) nor (3) would be applicable in such a mixture of anaerobic and aerobic waters, but would yield values smaller than the actual ΔN_2, especially if the sulphides are oxidized only to free sulphur instead of all the way to sulphates. The observed values of ΔN_2 and $N_2^{B(0)}$ in the aerobic zone indicate such an effect, although the differences are

larger than would be predicted. (Despite the fact that the Dramsfjord samples were 'poisoned' with mercuric chloride, it is possible that some free nitrogen was formed in the samples from the aerobic zone between the time of collection and analysis. However, the aerobic Cariaco Trench samples were stored without poisoning, and the values of ΔN_2 and $N_2^{B(0)}$ agree quite well). A similar mixing of aerated and anaerobic waters apparently accounts for the biogenic nitrogen found at 300 m in the Cariaco Trench.

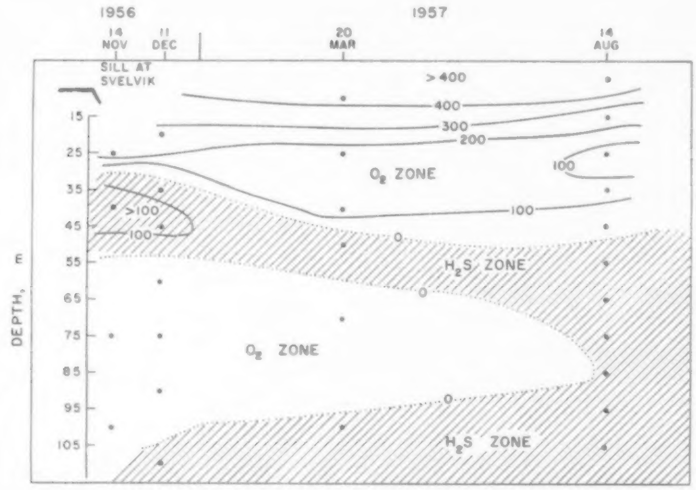

FIG. 3. Vertical distribution of sulphides and dissolved oxygen at station bm in the Dramsıjord, 14 November 1956–14 August 1957. Concentrations are in microgramme atoms per litre.

The hypothesis that biogenic nitrogen is released as dissolved gas is further substantiated by the fact that the nitrogen isotope ratio in the anaerobic zones is different from that in 'normal' aerobic sea-water. Although the accuracy of the calculated values for δ_B is low, it is believed that the difference in the mean values of 44‰ and 24‰ for the Cariaco Trench and the Dramsfjord is significant, a result which might be expected from the difference in the sources of organic material. Both values for δ_B are large compared with other values given in the literature. HOERING (1955), for instance, found a range of -13 to $+13$‰. Among the animal and plant proteins he analyzed, the largest value was 8·1‰ for seaweed from Tokyo Bay.

THE MECHANISM OF NITROGEN FORMATION

The anaerobic production of free N_2 from organic matter, in which it can be assumed that the nitrogen is present in the reduced (amino, $-NH_2$) form, is an overall oxidation, but the most probable pathway is *via* the reduction, or denitrification, of nitrate-nitrogen, since this is the only known metabolic pathway (FRY, 1955). However, direct anaerobic conversion of $-NH_2$ to N_2, with sulphate ion as the oxidant, might occur concurrently with, or subsequently to, the nitrate reduction. The data from the Cariaco Trench make it possible to examine this question, and to conclude that the direct oxidation does not take place.

Assume that the Cariaco Trench was at one time filled with water containing oxygen and nitrate in the approximate concentrations now found at sill depth (150 m) in the nearby open Caribbean, *i.e.*, about 7 μga/l of nitrate-nitrogen and 3 ml/l, or about 270 μga/l of dissolved oxygen. The disappearance of this quantity of oxygen would be accompanied by the oxidation of additional organic matter, giving rise to an additional 15 μga/l of nitrate-nitrogen (AOU : N = 270 : 15). Therefore, at the time the water became anaerobic the total nitrate-nitrogen available was 22 μga/l. The reduction of this nitrate to the observed zero would release 22 μga/l of free nitrogen, which is essentially equal to the observed mean value of ΔN_2 of 20·7 μga/l. It is evident that direct oxidation of amino-nitrogen to free nitrogen by sulphate does not *accompany* the reduction of nitrate, because otherwise ΔN_2 would be significantly larger. It is also unlikely that the sampling was carried out at the moment when the nitrate was all just reduced, and before direct oxidation could occur. Therefore, it follows within experimental errors, that direct oxidation does not take place. Were significantly higher concentrations of ΔN_2 present, it would be necessary to examine further the possibility of the direct oxidation.

The requirement for the intermediate formation of nitrate ion accounts for the essentially uniform distribution of biogenic nitrogen in the anaerobic part of the trench (just as the salinity is essentially uniform), although neither ammonia nor sulphides are uniformly distributed. The relatively high concentrations of ammonia now present have presumably accumulated from hydrolysis reactions (involving no oxidation of nitrogen), following the disappearance of the oxygen and nitrogen. Simultaneously, the oxidation of the organic residues, stripped of their amino groups, proceeds, with sulphate ions as the oxidant, giving rise to the accumulation of carbonates, phosphates and sulphides. Thus, there is no necessary relationship between the distribution of biogenic nitrogen and sulphides or ammonia, although there should be a direct relationship between the distribution of sulphides and ammonia.

Note added in proof.

The word " anaerobic " used in this paper and by RICHARDS and VACCARO (1956) is a misnomer since the word properly is applicable only to living bodies. The word ' anaeric (ally) ' was proposed by WILEN (WILEN, F., 1929. Use of the word " anaeric " proposed. *Ind.-Eng. Chem.*, News Ed. **1**, No. 17, p. 8) for the adjectival and adverbial motion of mere freedom from, or performance in the absence of, free oxygen. In describing this notion, the word ' anoxic ' appears more accurate, because the other gases found in air may be present. The words anoxic and anoxia, having a precedent in medical terminology, imply solely the absence of oxygen and their use is recommended.

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On the temperature, salinity, and density differences between the Atlantic and Pacific oceans in the upper kilometre*

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Abstract—The surface of the Pacific Ocean stands about 40 cm higher than the Atlantic Ocean with respect to the 1000-decibar surface, and the North Atlantic and North Pacific stand respectively about 14 and 17 cm higher than the South Atlantic and Pacific. The North Atlantic is warmest and saltiest, the South Atlantic is coldest and densest, and the North Pacific is least dense and least salty.

The extreme values in temperature and salinity of the North Atlantic are probably related to the formation of the deep water there, which carries away from the upper layer the cold water of relatively low salinity. If this water spreads into the South Atlantic at depth and is replaced with warm saline surface water from the South Atlantic via the South Equatorial Current and the Gulf Stream, then the South Atlantic should be substantially cooler and less salty.

The difference in density and sea level of the Atlantic and Pacific oceans may stem from the difference in latitude of the southern tips of America, Africa, and Australia, and the constriction of the west wind drift at Drake Strait. Only the densest surface waters of the Pacific pass through to the Atlantic, while lighter waters from lower latitudes of the South Atlantic pass eastward south of Africa. Further, the constriction of the flow by Drake Strait may result in a higher sea level on the Pacific side through the effect of *Windstau* (MONTGOMERY, 1938).

The density difference between the southern and northern oceans may be partly a consequence of the west wind drift around Antarctica. This is the greatest current of all oceans. Its flow is approximately geostrophically balanced and the surface slopes down to the south. The northern west wind drifts are not so strong, are at lower latitudes, and the high latitude flow is westward with slope upward to the north.

These differences are not confined to the upper thousand metres. The average density difference between the Atlantic and the Pacific from the surface to the bottom is about 17×10^{-5} g/cm^3. Referred to some deep surface such as 4000 decibars, the Pacific stands about 68 cm higher than the Atlantic.

INTRODUCTION

IN COMPUTING the geopotential at the sea surface with respect to the 1000-decibar surface in the Pacific, one arrives at values much higher than those for the corresponding latitudes of the Atlantic Ocean that were computed by DEFANT (1941). These differences must stem from differences in temperature and salinity. In the present paper the author has sought to locate the areas and levels of extreme difference. It seems worthwhile also to point out that certain features and processes in the ocean are consonant with the formation or the maintenance of these differences. The study of these features and processes might have led, and in some cases has led, to previous speculations that differences of this nature might exist.

THE DATA

Temperature and salinity data were read from various atlases. The *Meteor* Atlases (WÜST and DEFANT, 1936 ; BÖHNECKE, 1936) were used for the Atlantic. For the

*Contribution from the Scripps Institution of Oceanography, New Series.

Pacific the works of SCHOTT (1935), MUROMTSEV* (1958) and the NORPAC ATLAS (1960) were used. For surface temperatures the months of August and February were chosen for the northern and southern hemispheres, respectively, but since the salinity data in northern summer were more numerous and the seasonal variation is relatively small, BÖHNECKE's chart for June–July–August was used for the Atlantic and SCHOTT's chart for northern summer was used for the Pacific.

Table 1. *The area over which the averages were taken.*

Latitude	*North Atlantic*		*North Pacific*		*South Atlantic*		*South Pacific*	
	from	*to*	*from*	*to*	*from*	*to*	*from*	*to*
55–60	35W	10W	155W	140W	60W	20E	145E	75W
50–55	50	10	160E	135	60	20	145	75
45–50	50	5	155	130	60	20	145	75
40–45	60	10	145	125	60	20	150	75
35–40	75	10	140	125	60	20	150	75
30–35	75	10	125	120	50	15	155	75
25–30	75	15	125	115	50	15	155	70
20–25	75	15	125	115	40	10	150	70
15–20	60	15	120	100	35	10	150	80
10–15	60	15	120	100	35	10	150	80
5–10	50	15	130	80	35	10	150	80
0–5	50	10E	130	80	35	10	150	80

Average values were estimated by eye in areas five degrees on a side in the Atlantic and North Pacific. South of 20 °N in the Pacific averages were taken from areas ten degrees on a side. The five-degree areas were then combined into ten-degree areas and all were expressed as the averages in ten-degree zones of latitude for each ocean.

The levels chosen were 0, 200, 400, 600 and 1000 metres. These are of course not adequate to make good vertical averages but they serve to describe the levels and zones of greatest differences.

The density was obtained in two ways. For each latitudinal zone at each level the average temperature and salinity were used to calculate σ_t (Tables 2 and 3) which is defined as $(\rho_{s,t,0} - 1)\,1000$ where $\rho_{s,t,0}$ is the density in g/cm^3 of water of the appropriate temperature and salinity but at a pressure of one atmosphere. Since the coefficient of thermal expansion increases with temperature, density computed from an average of two temperatures will be greater than the average of the densities at the two temperatures. Values of σ_t as tabulated are too large by amounts up to 0·20. Greatest errors will occur where the maximum temperature and its range are both high ; that is, at the surface in the tropics. These particular values are included so that the densities at the various zones and depths may be compared. At each of the five depths the mean value of σ_t in each ocean has been calculated (Table 3) but no vertical averages of σ_t were calculated.

The other method of obtaining density was to convert the computed geopotential distance from the zero- to the 1000-decibar surface to average specific volume and

*It is not Muromtsev's tabulated averages which are used here, but the charts in his atlas (1958, Appendix II). Since the Atlantic values were to be estimated by eye from charts it was thought best to use the same method, with the same number of depths, in the Pacific. Muromtsev has used all of the material available to him in 1954 and has prepared averages by Marsden squares, by depth, and by month (1958, Appendix I). His tables are far more detailed and inclusive than those prepared here, and if similar tables were available for the Atlantic a more detailed comparison could be made.

Table 2. Average temperature, salinity, and σ_t by ten-degree bands by depth. (The means listed are the depth-integrals of the tabulated values, divided by 1000 *metres. σ_t is computed at each level and latitude from the tabulated salinity and temperature).*

A. Atlantic

	50°–60 °N			40°–50 °N			30°–40 °N			20°–30 °N		
	T,°C	S,‰	σ_t	T,°C	S,‰	σ_t	T,°C	S,‰	σ_t	T,°C	S,‰	σ_t
0	11·06	35·04	26·82	18·04	34·94	25·24	25·17	36·43	24·36	26·52	36·79	24·24
200	6·56	35·06	27·56	11·47	35·49	27·08	17·13	36·27	26·48	18·76	36·56	26·30
400	6·36	35·06	27·58	10·16	35·39	27·25	14·99	36·06	26·82	15·30	36·07	26·75
600	5·41	35·03	27·67	8·79	35·30	27·41	13·02	35·64	26·90	10·94	35·63	27·29
1000	4·35	34·97	27·75	5·33	35·18	27·80	8·17	35·37	27·57	6·74	35·09	27·55
Mean	6·18	35·03		9·83	35·30		14·48	35·88		14·09	35·91	

	10°–20 °N			0°–10 °N			0°–10 °S			10°–20 °S		
0	26·92	35·84	23·40	24·53	34·96	24·06	26·70	35·89	23·51	24·68	36·76	24·80
200	15·58	36·10	26·72	12·40	35·21	26·69	12·45	35·19	26·67	14·24	35·43	26·49
400	11·03	35·28	27·01	8·40	34·76	27·05	8·32	34·74	27·04	8·70	34·73	26·98
600	8·14	34·96	27·24	6·05	34·59	27·24	5·49	34·51	27·25	5·55	34·42	27·18
1000	5·30	34·85	27·55	4·56	34·65	27·45	4·05	34·59	27·48	3·70	34·54	27·47
Mean	11·52	35·32		9·34	34·80		9·28	34·85		9·46	34·94	

	20°–30 °S			30°–40 °S			40°–50 °S			50°–60 °S		
0	23·79	36·14	24·59	20·73	35·37	24·87	10·85	(34·28)	26·26	3·15	(33·89)	(27·01)
200	15·20	35·49	26·34	13·06	35·16	26·52	5·46	34·24	27·04	1·26	34·33	27·52
400	10·76	34·92	26·78	9·91	34·83	26·85	3·75	34·21	27·21	1·71	34·55	27·66
600	6·71	34·53	27·11	6·27	34·47	27·11	2·97	34·24	27·30	1·61	(34·64)	27·74
1000	3·50	34·44	27·41	3·40	34·28	27·29	2·66	34·41	27·45	(0·40)	34·68	27·85
Mean	10·28	34·94		9·23	34·73		4·35	34·27		1·47	34·49	

B. Pacific

	50°–60 °N			40°–50 °N			30°–40 °N			20°–30 °N		
	T,°C	S,‰	σ_t	T,°C	S,‰	σ_t	T,°C	S,‰	σ_t	T,°C	S,‰	σ_t
0	10·01	32·63	25·12	14·61	33·03	24·56	23·07	34·28	23·39	25·45	34·98	23·21
200	4·24	33·85	26·87	5·77	33·82	26·68	12·69	34·23	25·87	16·26	34·65	25·44
400	3·80	34·10	27·11	4·60	34·00	27·05	9·10	34·23	26·53	11·04	34·30	26·24
600	3·54	34·26	27·26	3·83	34·16	27·16	5·88	34·09	26·87	6·99	34·18	26·80
1000	2·82	34·42	27·45	3·01	34·37	27·40	3·62	34·31	27·29	3·90	34·41	27·34
Mean	4·24	34·02		5·29	33·99		9·15	34·21		10·88	34·42	

	10°–20 °N			0°–10 °N			0°–10 °S			10°–20 °S		
0	27·06	34·42	22·30	27·24	34·26	22·11	26·54	35·16	23·01	26·43	35·60	23·37
200	15·70	34·73	25·63	12·90	34·84	26·31	16·50	35·25	26·07	19·60	35·59	25·34
400	9·30	34·46	26·66	9·10	34·71	26·89	10·10	34·73	26·75	10·90	34·77	26·63
600	6·50	34·45	27·07	6·90	34·61	27·14	7·10	34·61	27·11	7·00	34·58	27·11
1000	4·40	34·54	27·40	4·70	34·57	27·39	4·60	34·54	27·38	4·20	34·52	27·41
Mean	10·54	34·52		10·13	34·63		11·02	34·80		11·68	34·91	

	20°–30 °S			30°–40 °S			40°–50 °S			50°–60 °S		
0	24·12	35·61	24·08	19·83	35·06	24·86	13·50	34·39	25·84	7·03	33·96	26·62
200	17·90	35·42	25·64	12·10	34·91	26·52	7·90	34·59	26·98	4·80	34·41	27·25
400	11·50	34·70	26·47	8·60	34·60	26·89	6·70	34·42	27·04	3·80	34·24	27·22
600	7·20	34·47	26·98	6·90	34·42	27·10	6·20	34·37	27·05	3·60	34·34	27·32
1000	4·60	34·43	27·28	4·70	34·38	27·24	4·50	34·37	27·25	2·90	34·43	27·46
Mean	11·37	34·81		9·13	34·61		7·03	34·43		4·08	34·31	

then to average density. Charts of this quantity (the depth integral of the specific volume) were available for both the Atlantic (DEFANT, 1941, BEILAGE XIV) and for the Pacific* (REID, manuscript in preparation), and the horizontal averages were obtained in a similar manner to that used for the salinity and temperature. Both the Atlantic and the Pacific charts of geopotential contain materials from all months of the year and from many different years. They show the same tendency for high-latitude observations to be made in summer and low-latitude observations throughout the year.

Table 3. Average temperature, salinity, and σ_t by depth. The relative width of the ocean in each zone was taken into account in calculating these values from those in Table 2. These values of σ_t were also calculated from Table 2, not from the adjacent temperature and salinity in this table. The means listed below each column are the depth-integrals of the tabulated values divided by 1000 metres.

	Temperature °C			*Salinity, ‰*			σ_t		
Depth	*North Atlantic*	*North Pacific*	△	*North Atlantic*	*North Pacific*	△	*North Atlantic*	*North Pacific*	△
0	23·30	23·80	− 0·50	35·84	34·26	+ 1·58	24·27	22·88	+ 1·39
200	16·30	13·20	+ 3·10	35·91	34·56	+ 1·35	26·68	25·97	+ 0·71
400	11·72	8·91	+ 2·81	35·48	34·38	+ 1·10	26·98	26·65	+ 0·33
600	9·31	6·26	+ 3·05	35·19	34·36	+ 0·83	27·23	27·01	+ 0·22
1000	5·99	4·09	+ 1·90	35·00	34·47	+ 0·53	27·54	27·37	+ 0·17
Mean	11·78	9·58	+ 2·20	35·42	34·42	+ 1·00	26·84	26·39	+ 0·45
	South Atlantic	*South Pacific*	△	*South Atlantic*	*South Pacific*	△	*South Atlantic*	*South Pacific*	△
0	19·25	20·91	− 1·66	35·48	35·06	+ 0·42	24·98	24·50	+ 0·48
200	10·91	14·00	− 3·09	34·98	35·03	− 0·05	26·72	26·18	+ 0·54
400	7·54	9·01	− 1·47	34·67	34·61	+ 0·06	27·05	26·80	+ 0·25
600	4·95	6·50	− 1·55	34·45	34·48	− 0·03	27·25	27·08	+ 0·17
1000	3·15	4·31	− 1·16	34·48	34·45	+ 0·03	27·48	27·34	+ 0·14
Mean	7·73	9·51	− 1·78	34·71	34·67	+ 0·04	26·92	26·64	+ 0·28

The area over which the averages were taken (Table I) excludes the Caribbean Sea and the Gulf of Mexico because the *Meteor* Atlas did not include them. The latitudes above 60° were left out partly because of the sparseness of the data and partly because in the far north the two oceans are not really comparable in depth or in circulation.

LIMITATIONS

Averages of this sort could best be made by some form of machine data processing in which more data and data at closer depth intervals could be used. Since temperature and salinity data for standard levels such as 10, 25, 50, 75, 100, and 150 metres were not available in the form of charts for the Atlantic, these levels were not included for the Pacific either. As a test of the sort of errors in the mean that might result from a linear interpolation from zero to 200 metres the area from 150° to 160 °W longitude was examined again by ten-degree zones from 0° to 60 °N, including data at 25, 50, 100, and 150 metres. In the average from 0 to 1000 metres no changes greater

*The materials used in preparing the Pacific chart include 1750 stations. A listing of the stations and a station pattern will be included when the chart is published.

Table 4. Average temperature, salinity, density ($\rho_{s,t,p}$), and geopotential anomaly (at the sea surface with respect to the 1000-decibar surface) by latitudinal bands. In computing the means the relative width of the ocean in each zone was taken into account. The density was computed from the geopotential anomaly, which had been calculated from individual stations, not from the σ_t averages of Table 2. Both density and geopotential are tabulated, since the latter may be used directly to estimate variations of sea level with respect to the 1000-decibar surface.

	Temperature, °C			Salinity, ‰			Density, g/cm³			Geopotential Anomaly (dynamic metres)		
Latitude	*Atlantic*	*Pacific*	△	*Atlantic*	*Pacific*	△	*Atlantic*	*Pacific*	△	*Atlantic*	*Pacific*	△
50°–60 °N	6·18	4·24	1·94	35·03	34·02	1·01	1·02986	1·02935	51	0·60	1·08	− 0·48
40°–50 °N	9·83	5·29	4·54	35·30	33·99	1·31	1·02946	1·02923	23	0·98	1·20	− 0·22
30°–40° N	14·48	9·15	5·33	35·88	34·21	1·67	1·02911	1·02876	35	1·31	1·65	− 0·34
20°–30 °N	14·09	10·88	3·21	35·91	34·42	1·49	1·02903	1·02846	57	1·38	1·92	− 0·54
10°–20 °N	11·52	10·54	0·98	35·32	34·52	0·80	1·02907	1·02862	45	1·35	1·77	− 0·42
0°–10 °N	9·34	10·13	− 0·79	34·80	34·63	0·17	1·02911	1·02872	39	1·32	1·68	− 0·36
Mean	11·78	9·58	2·20	35·42	34·42	1·00	1·02915	1·02872	43	1·27	1·68	− 0·41
0°–10 °S	9·28	11·02	− 1·74	34·85	34·80	0·05	1·02917	1·02872	45	1·25	1·68	− 0·43
10°–20 °S	9·46	11·68	− 2·22	34·94	34·91	0·03	1·02913	1·02862	51	1·29	1·77	− 0·48
20°–30 °S	10·28	11·37	− 1·09	34·94	34·81	0·13	1·02907	1·02873	34	1·35	1·67	− 0·32
30°–40 °S	9·23	9·13	0·10	34·73	34·61	0·12	1·02913	1·02899	14	1·29	1·42	− 0·13
40°–50 °S	4·35	7·03	− 2·68	34·27	34·43	−0·16	1·02951	1·02923	28	0·93	1·20	− 0·27
50°–60 °S	1·47	4·08	− 2·61	34·49	34·31	0·18	1·02997	1·02959	38	0·50	0·86	− 0·36
Mean	7·73	9·51	− 1·78	34·71	34·67	0·04	1·02930	1·02889	41	1·13	1·51	− 0·38

than 0·10‰ were found in salinity. In temperature, however, systematic changes resulted from the nature of the thermal structure. Values too high by as much as 0·37 °C were found north of 20 °N, and values too low by 0·21 °C and 0·54 °C in the areas from 10° to 20 °N and 0° to 10 °N, respectively. This last error is a consequence of the great thickness of the mixed layer between the Equatorial Current and Countercurrent. A similar thermal feature is found in the corresponding latitudes of the Atlantic on *Meteor* stations 213, 258, 259, 261 and 297.

Since temperature data from the summer season were used in all oceans the errors may tend to cancel each other when differences are taken by latitude. In any case the horizontal averages (Tables 2 and 3) are unaffected by this sort of error, and the differences of temperature (Table 4) are in all but one case large compared with the maximum error found. The temperature anomalies of the two Atlantic oceans are large compared with the maximum error (Table 5). The Pacific anomalies are very small and cannot be much increased by the systematic errors found in the test area.

Table 5. Average temperature, salinity, density ($\rho_{s,t,p}$) and geopotential anomaly (at the sea surface with respect to the 1000-decibar surface) of the upper kilometre of the Atlantic and Pacific oceans between 60° N and 60 °S latitude, and the deviations from the average in four areas. Both density and geopotential are tabulated, since the latter may be used directly to estimate variations of sea level with respect to the 1000-decibar surface.

		T, °C	S, ‰	$\rho_{s,t,p}$ g/cm³	*Geopotential Anomaly (dynamic metres)*
Mean		9·55	34.70	1·02894	1·47
Atlantic	*North*	+ 2·23	+ 0·72	$+ 21 \times 10^{-5}$	− 0·20
	South	− 1·82	− 0·01	$+ 36 \times 10^{-5}$	− 0·34
	Mean	+ 0·03	+ 0·32	$+ 30 \times 10^{-5}$	− 0·28
Pacific	*North*	+ 0·03	− 0·28	$- 22 \times 10^{-5}$	+ 0·21
	South	− 0·04	− 0·03	$- 04 \times 10^{-5}$	+ 0·04
	Mean	− 0·01	− 0·15	$- 13 \times 10^{-5}$	+ 0·12
Mean of North Atlantic and North Pacific		+ 0·68	+ 0·02	$- 09 \times 10^{-5}$	+ 0·09
Mean of South Atlantic and South Pacific		− 0·58	− 0·02	$+ 07 \times 10^{-5}$	− 0·07

Calculations of the geopotential anomaly (from which, in turn, density was calculated) were made for individual stations using data from about 16 depth intervals. These results are undoubtedly more accurate than the temperature and salinity averages over depth. They may suffer somewhat through the inadequate knowledge of the equation of state of sea water (ECKART, 1958 ; 1959). R. O. REID'S (1959) examination of the problem suggests that errors in the pressure dependent terms, which are the most inaccurately known, should result in negligibly small errors in the differences in the upper thousand metres. Probably the density differences found here are gross enough to remain relatively unchanged after refinement of the equation of state, but this limitation must be kept in mind.

THE RESULTS

Over the greater part of the Atlantic and Pacific oceans (Table 1) the temperature and salinity have been averaged at various depths in each zone (Table 2) and by depth (Table 3) and by zone (Table 4) for each ocean, and the average values for the various oceans have been compared (Table 5). In each table the appropriate values of σ_t, density, or geopotential have been included.

With respect to the 1000-decibar surface the Pacific Ocean stands 40 cm higher than the Atlantic, and the North Pacific and North Atlantic stand, respectively, 17 and 14 cm higher than the South Pacific and South Atlantic (Table 5). The North Atlantic is warmest and saltiest, the South Atlantic is coldest and densest, and the North Pacific is least dense and least salty.

In the upper thousand metres the South Atlantic's high density is the result of its low temperature. This may be partly the consequence of the ratio of high-latitude to low-latitude area there. The low density of the North Pacific is the result of its low salinity. The North Atlantic, although the warmest of the oceans in its upper thousand metres, is denser than the mean because of its great salt content.

The effect of the ratio of high-to-low latitude area is not present in the averaging in Table 4, where it is seen that the North Atlantic is warmer at every latitude than the South Atlantic and is the warmest of all oceans at latitudes above 20°. It is most saline at all latitudes above 10°. The South Atlantic is densest at all latitudes. The North Pacific is least saline at all latitudes and is at no latitude denser than any other ocean.

DISCUSSION

Some of these simple results were among the earliest findings in physical oceanography, yet they have received remarkably little attention. Von Boguslawski (1884) refers to the results of the *Challenger*, *Tuscarora*, and *Gazelle* measurements, which indicate (Von Boguslawski, 1884, p. 250, my translation) ' Between the upper water layer influenced by radiation, which reaches a depth of 110 to 160 m, and a depth of 2750 m or 1500 fathoms, all the water of the North Atlantic is warmer than the water of the South Atlantic at the same depth and latitude.' (The data he compares extend from 42 °N to 42 °S in the Atlantic and do not reach below 2750 m). He writes also (p. 310, my translation) ' The water of the North Pacific is in its total mass colder than that of the North Atlantic ' and ' The water of the South Pacific is to 1300 m (about 700 fathoms) depth warmer than the South Atlantic, beneath this depth colder.'

Krümmel (1907) calculated mean values of temperature for the separate oceans. Since his values of temperature are for the total volume of the ocean (p. 495) they are not directly comparable to the results of this paper. He finds, however, that the North Atlantic is warmest (except for the North Indian Ocean), the South Atlantic is coldest, and the North and South Pacific are about equal and intermediate. He does not make vertical averages of salinity but his tabulations at various depths (p. 337) indicate that in the upper kilometre the North Atlantic is saltiest, the North Pacific least salty, and the South Atlantic and South Pacific about equal.

SEA LEVEL AND DENSITY

Levelling surveys (Rappleye, 1932) indicate that along the Pacific Coast of the United States mean sea level is about 50 cm higher than along the Atlantic Coast,

and that across the Panama Canal Zone ' mean sea level at Balboa along the Pacific Coast is about 3/4 foot higher than mean sea level on the Atlantic Coast ' (U.S.C.G.S., personal communication). SVERDRUP *et al.* (1942, p. 459) speculated that ' this difference may perhaps be related to the lower average density of the Pacific water.' It is possible that this speculation was made also in the light of the *Carnegie* data (FLEMING *et al.*, 1945), with which SVERDRUP was working at that time and which he might have compared with DEFANT's (1941) chart.

Of processes which might contribute to the difference, or the maintenance of the difference, in density and sea level between the Atlantic and Pacific oceans, two can be mentioned. One is related to the difference in the southern limits of South America (56 °S), Africa (35 °S) and Australia (44 °S). The other is related to the constriction of the west wind drift around Antarctica by Drake Strait.

As a consequence of the first, the water from only the southernmost one-fifth of the South Pacific passes through Drake Strait, while the southern half of the South Atlantic may flow eastward into the Indian Ocean. In southern summer the average surface density (σ_t) between 50° and 60 °S in the Pacific is 26·62 (Table 2). In the South Atlantic the average σ_t of the zones between 30° and 40°, 40° and 50°, and 50° and 60 °S are 24·87, 26·26, and 27·01, respectively. The South Atlantic may lose surface water of an average σ_t of about 26·05 and gain water of about 26·62 from the Pacific. The South Pacific may lose water of about 26·62 to the Atlantic and gain water from the Indian Ocean south of 44° S whose average surface σ_t between 45° and 60 °S is about 26·25 in southern summer according to SCHOTT (1935). This is about the same as for the zone between 40° and 60 °S in the Pacific.

The other process is best stated by quoting from MONTGOMERY (1938) who writes (p. 170, second footnote), ' Imagine a canal encircling the earth in the zone of westerly winds, and let there be a constriction at one part of the canal ; sea level would be higher at the western end of this constriction than at the eastern end due to *Windstau*. This is essentially the case in the Southern Ocean and the constriction occurs at Drake Strait, sea level being higher on the Pacific side and lower on the Atlantic side (presumably!), accounting for the probable fact that the Pacific Ocean is generally at a higher level than the Atlantic.' He then cites the U.S.C.G.S. measurements of different sea level on the Atlantic and Pacific coasts of the United States.

Some part of the north-south difference in density and sea level might have been expected as a consequence of the difference in circulation. Given the observed distribution of the surface currents of the oceans, and assuming approximate geostrophic equilibrium, one might expect that the average sea level in the regions of the west wind drifts might be lower in the southern hemisphere than in the northern. The flow around Antarctica is stronger and is eastward everywhere except in part of the Weddell Sea. For the flow to be in geostrophic balance a steep slope downward to the south must exist, with the slope proportional to the velocity and to the sine of the latitude. The northern west wind drifts (North Pacific and North Atlantic Currents) are not so strong and occur at lower latitudes. Westward flow occurs at higher latitudes (Alaska Current and East Greenland Current) with slopes upward to the North.

The highest values of temperature and salinity are found in the North Atlantic Ocean. Although the extremely warm and saline waters (about 12 °C and 38‰) of the Mediterranean undoubtedly contribute to the high values of the upper kilometre

of the North Atlantic, the effect is lessened by their high density, which causes them to sink very rapidly as they mix. Little direct evidence of their presence is seen on the horizontal distributions of salinity and temperature above 800 metres (WÜST and DEFANT, 1936), and the effect of the Mediterranean water is most apparent over large areas on the charts at 1500 and 1750 metres. WÜST (1935, Tabelle 19) estimates the Mediterranean water at $36 - \frac{1}{4}$ °N $6 - \frac{3}{4}$ °W to be at 600 to 700 metres and to be of 11·9 °C and 36·5 ‰. The σ_t of such water is 27·82 and it is more dense than the average at 1000 metres in the zone 30°– 40 °N (Table II). The horizontal charts indicate that in the upper thousand metres the water of high density originates at higher latitude than the Straits of Gibraltar.

A process which has quite different effects in the North Pacific and the North Atlantic is the sinking of surface water in winter. Only intermediate water of low salinity is formed in the North Pacific while much saltier deep water is formed in the North Atlantic. The North Pacific thus retains within the upper thousand metres of the subtropical anticyclonic gyre the product of the precipitation and cooling of its high latitudes. The analogous water is eliminated from the upper thousand metres of the North Atlantic when it sinks to depths greater than 2000 metres. The difference is a consequence of the low salinity at the surface in high latitudes in the North Pacific (32·63‰) which limits the surface density to about 1·02609 g/cm^3 (Table 2) and the high salinity at the surface in the high latitude Atlantic (35·04‰) which permits the surface density to rise above 1·02775 g/cm^3 over large areas in winter. The surface water of the North Pacific thus remains in the upper thousand metres, while part of the surface water of the North Atlantic sinks to more than 2000 metres, forming the North Atlantic Deep Water and removing a large part of the precipitation from the surface.

The North Atlantic Deep Water extends southward and supplies a great part of the water in the South Atlantic. Since South Atlantic surface water flows from the South Equatorial Current along the north coast of South America, the South Atlantic contributes a part of its warm water to the North Atlantic. This, in turn, accounts in part for the low temperature of the South Atlantic.

Another important consideration is the temperature of the surface water entering and leaving the South Atlantic in the west wind drift. In a like manner to that used for the density it can be estimated that in southern summer the average temperature of the incoming surface water is not more than 7 °C, while the outgoing water ranges from 3·2° to 21 °C, with a mean of about 9·7 °C.

The surface water passing Drake Strait is only about 34‰ in salinity while the average between Africa and 60 °S is about 34·40‰. That passing between Australia and 60 °S is about 34·40‰ (SCHOTT, 1935). If other effects could be neglected one would expect the South Atlantic to be less saline than the South Pacific, but this is clearly not the case (Table V).

THE DIFFERENCES AT GREATER DEPTHS

MONTGOMERY (1958), COCHRANE (1958), and POLLAK (1958) have computed the mean potential temperature, salinity, and potential specific volume anomaly of the Atlantic, Pacific, and Indian oceans, respectively, and MONTGOMERY'S work combines the results for the world ocean. These figures, which are for the total volume of the ocean, indicate that the potential specific volume anomaly of the Atlantic is less than

that of the Pacific by 17×10^{-5} cm^3/g. This may be taken roughly as a density difference of 17×10^{-5} g/cm^3, with the Atlantic being heavier. This is about half the difference in density in the upper kilometre, and implies, as might be expected, that the density differences decrease with depth. However, it implies also that the deeper densities are also greater in the Atlantic, that the 1000-decibar surface also stands higher in the Pacific, and that with respect to some deep pressure surface, such as 4000 decibars, the Pacific sea surface must stand 68 cm higher than the Atlantic.

Montgomery (1958) finds the average potential temperature (from the surface to the bottom) to be 0·37 °C higher in the Atlantic than the Pacific. This is greater than the difference in the upper thousand metres and implies that the differences increase at greater depths. A comparison of the charts of Wüst and Defant (1936) and Muromtsev (1958) confirms this. Montgomery finds the salinity to be greater in the Atlantic by 0·28‰ This is less than in the upper thousand metres.

For the Pacific Ocean Cochrane (1958) has calculated the average potential temperature (again from the surface to the bottom) and found the North and South Pacific to differ by only 0·02 °C. He finds the salinity of the South Pacific to be 0·05‰ higher than the North Pacific. This is about one-fifth of the difference in the upper thousand metres and implies that the deeper salinities are not significantly different. He finds the potential specific volume anomaly to be 5×10^{-5} cm^3/g higher in the North Pacific. If this is taken to represent roughly a density difference of 5×10^{-5} g/cm^3, with the North Pacific lighter, then it is about a third of the difference in the upper thousand metres and implies that the density differences extend somewhat deeper.

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Nutrients limiting the production of Phytoplankton in the Sargasso Sea, with special reference to iron

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Abstract—The effects of enriching surface water samples from the Sargasso Sea upon the rate of C^{14} assimilation was investigated. The addition of nitrate, phosphate and vitamins, added separately or in combination, had no stimulatory effect, while addition of a trace metal mixture increased C^{14} uptake by several-fold. The effective component of the trace metal mix was found to be iron, which alone enhanced C^{14} uptake for 24 hours but which required the addition of nitrogen and phosphorus to produce a comparable effect over a three-day period.

INTRODUCTION

CORRELATION between the nitrogen and phosphorus content of surface waters and the rate of organic synthesis has been demonstrated repeatedly in temperate seas (KETCHUM *et al*, 1958). This coupled with the fact that the large, central, relatively unproductive areas of the ocean often contain negligible quantities of these elements in their euphotic zone has led to the general belief that primary production is directly limited by supplies of nitrate and phosphate.

HARVEY (1926) first noted that nitrogen and phosphorus decreased together and at a constant ratio during the spring diatom maximum in the waters of the English Channel. He suggested that the two elements became limiting to plant production simultaneously . REDFIELD (1934) enlarged upon this theory extending it to the oceans as a whole. He observed that these elements are depleted from sea water in very nearly the same ratio as they occur in plankton (15 N : 1 P by atoms).

Statistically, over the oceans as a whole and at all depths, the concentrations of these elements occur at the same ratio, but values lower than this have consistently been recorded in surface waters. RILEY and CONOVER (1956), for example, reported a value of 8 : 1 in Long Island Sound, while repeated observations at Bermuda by the authors have shown an average value of 10 : 1. This has led to the belief that nitrogen rather than phosphorus is the more important limiting factor in these waters (KETCHUM et *al*, 1958).

Recent attempts by the authors (MENZEL and RYTHER, 1960) to correlate both the concentrations and rates of removal of nitrate and phosphate with plant growth in the Sargasso Sea have been unsuccessful. Accepting the thesis that these elements are truly limiting, two explanations may be offered for this lack of correlation : (1) the instantaneous concentration of their organic forms does not give an index as to their general availability, but rather the rate of their regeneration determines the level of production that may be attained, or (2) vertical diffusion accounts for the enrichment of surface waters. This enrichment however may never be reflected by changes in the absolute concentration of nitrate and phosphate since the nutrients

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may be utilized by plants as rapidly as they become available. Unfortunately little is known of the natural rate or quantitative significance of either of these processes and therefore their relative importance remains one of speculation.

A possible alternative explanation for lack of correlation between nitrogen and phosphorus and primary production is that these two elements are not in themselves primary limiting factors to production in these waters. Indications that this might actually be the case have been provided by HENTSCHEL (1932), STEEMANN NIELSEN and JENSEN (1957), CURRIE (1958), and RYTHER and GUILLARD (1959) when they, using the direct approach of enrichment procedure, found no increase in photosynthetic rates in samples of sea water to which nitrogen and phosphorus had been added. On the other hand, RYTHER and GUILLARD (loc. cit.) found that phytoplankton growth in the Sargasso Sea was enhanced by the addition of a combination of trace metals and iron. The problem remained then of attempting to isolate the critical element or elements within this mixture.

METHODS

The experiments described below were carried out during October, 1959 when the concentration of nutrients in the euphotic zone of the Sargasso Sea was minimal. Surface water was collected from a point 15 miles south of Bermuda. This was dispensed into a number of one-litre bottles and enriched with a combination of nutrients. These bottles were then placed in an incubator cooled with running sea water and exposed to a constant light source (fluorescent) of 1500 foot candles. At the end of the first 24 hours two aliquots of 150 ml each were withdrawn from each bottle and inoculated with approximately 15 μ curies of $C^{14}O_3$. One of these aliquots was then exposed to the same light source and the other placed in darkness for a period of four hours. After this time they were filtered through HA millipore filters, rinsed with ·01 N HCl, dried and the activity measured in a gas flow geiger counter. Additional aliquots were withdrawn after a period of 72 hours and treated in a similar manner. Results given in the following discussion were corrected for uptake in the dark.

*Table 1. Media used in enrichment experiments**

1. KNO_3	50 μ gA/L N
2. KH_2PO_4	5 μ gA/L P
3. Vitamin Mix	
Thiamin. HCl	0·2 mg/L
Biotin	1·0 μ g/L
B_{12}	1·0 μ g/L
4. Iron-trace Metal Mix	
FeNaEDTA	0·13 mg/L Fe
$CuSO_4 \cdot 5\,H_2O$	0·005 mg/L Cu
$ZnSO_4 \cdot 7\,H_2O$	0·010 mg/L Zn
$CoCl_2 \cdot 6\,H_2O$	0·005 mg/L Co
$MnCl_2 \cdot 4\,H_2O$	0·100 mg/L Mn
$Na_2MoO_4 \cdot 2\,H_2O$	0·005 mg/L Mo
5. $FeCl_3$	0·13 mg/L Fe
6. Na_2EDTA	1·0 mg/L

**Items 1–4 inclusive constitute complete media used except where indicated in the text.*

The nutrients used in these experiments are similar to those used routinely in the laboratory for the culture of marine phytoplankton. The complete media consisted of nitrate, phosphate, vitamins and trace metals with iron (Table 1). The experimental approach used was : (1) to enrich

samples with the complete media lacking one or more of the major groups (i.e. N and P, metals, vitamins) thus permitting assay of the relative importance of groups of elements, (2) subtracting one element at a time ftom the larger group observed to directly affect the rate of photosynthesis, (3) adding the critical element or elements to samples singly or in combination until all controlling factors were isolated.

RESULTS

Table 2 shows the results of experiments that were concluded after phytoplankton had been exposed to enriched waters for a period of 24 hours. Although changes in relative photosynthesis were not large, values consistently higher than the control

Table 2. Relative uptake of C^{14} (4-hour experiments) by enriched surface water after 24 hours. Values relative to C^{14} uptake in unenriched controls: i.e. *experimental/control*

	Experiment Number		
	(1)	(2)	(3)
Complete Media	1·8	1·6	2·0
Nitrate + Phosphate + Metals	2·0	1·7	2·7
Metals	2·0	1·7	2·4
Vitamins	1·0	1·0	—
Nitrate + Phosphate	0·7	1·0	0·9

were demonstrated only in those samples to which metals had been added. The addition of nitrogen and phosphorus alone, or in combination with vitamins apparently had no effect on photosynthesis.

When these experiments were extended for a period of 72 hours, however, the effect of adding the trace-metal iron complex alone was not apparent (Table 3). Here it became obvious that lacking nitrogen and phosphorus, enriched samples

Table 3. Relative uptake of C^{14} (4-hour experiments) by enriched surface water after 72 hours. Values as in Table 2

	Experiment Number				
	(1)	(2)	(3)	(4)	(5)
Complete Media	18·7	13·6	14·3	—	—
Nitrate + Phosphate + Metals	16·1	12·6	11·5	12·7	11·6
Metals	1·2	1·0	1·3	—	—
Nitrate + Phosphate + Vitamins	1·2	1·1	1·2	—	—
Nitrate + Phosphate	0·9	0·8	1·3	1·5	1·0
Vitamins	1·1	0·9	—	—	—

were not capable of any further growth than that shown at the end of 24 hours. The initial stages of this work, however, also exhibited the fact that the addition of nitrogen and phosphorus without the inclusion of the trace metal complex also had no apparent effect on growth. It seemed obvious then that growth was dependent upon nitrogen, phosphorus, and one or more elements of the trace-metal complex.

The results of experiments designed to isolate the limiting factor from the mixture of metals are given in Table 4. They show clearly that little effect was evidenced except where iron was present in the media, and thus demonstrate that iron was

Table 4. Relative uptake of C^{14} (4-hour experiments) by surface water enriched with nitrate, phosphate and metals but omitting the metal indicated, after 72 hours. Values as in Table 2

	Experiment Number				
	(1)	(2)	(3)	(4)	(5)
Copper	13·0	9·2	—	—	—
Zinc	17·2	11·5	—	—	—
Manganese	8·8	19·6	—	—	—
Cobalt	1·9	12·0	11·9	11·5	10·9
Molybdate	10·0	18·1	—	—	—
Iron	1·0	1·1	1·1	1·1	1·1

critically limiting in these experiments. Nitrogen and phosphorus however very rapidly became limiting when iron was added in excess, as is evidenced from the fact that the effect of metal enrichment alone was measured only within the first 24 hours.

Since iron was added as FeNaEDTA, the possibility remained that the chelating action of this compound and not its iron fraction was responsible for the results obtained. This was tested by (1) enriching samples with iron in the form of its chloride

Table 5. Relative uptake of C^{14} (4-hour experiments) by surface water enriched with various forms of iron and EDTA *after* 72 *hours. Values as in Table* 2

	Experiment Number					
	(1)	(2)	(3)	(4)	(5)	(6)
Nitrate + Phosphate + FeNaEDTA	11·9	11·6	13·8	14·6	7·6	6·3
Nitrate + Phosphate + $FeCl_3$	7·8	6·9	10·2	10·4	—	—
Nitrate + Phosphate + Na_2EDTA	1·3	1·1	0·8	0·9	—	—

and (2) enriching samples with amounts of Na_2EDTA equivalent to that added when using FeNaEDTA. Table 5 provides evidence that iron and not the NaEDTA fraction of the molecule was responsible for increasing the rate of carbon uptake.

OBSERVATIONS BETWEEN BERMUDA AND THE WEST INDIES

To test whether iron is limiting in semi-tropical oceanic waters in general, a series of enrichment experiments were conducted on an oceanographic cruise (R.V. *Crawford* 37) between Bermuda and the West Indies. The technique used in this procedure was essentially the same as that described above except that enrichment

was carried out only with nitrate plus phosphate alone and in combination with iron. In addition the samples were incubated in full daylight and not under constant artificial light.

Table 6. Relative uptake of C^{14} (4-hour experiments) by enriched surface water in passage from Bermuda to the West Indies. Values as in Table 2

Position	*Enrichment Media*	
	$NO_3 - N + PO_4 - P$	$NO_3 - N + PO_4 - P + Fe$
32 12′N 64 24′W	0·8	4·1
29 50·N 59 43′W	0·7	5·2
28 13·N 45 58′W	1·3	3·1
28 01′N 53 54′W	1·0	5·9
27 58′N 50 31′W	1·5	3·9
27 39′N 48 48′W	4·4	2·8
26 21′N 45 29′W	1·0	2·7
26 01′N 47 51′W	1·0	5·1
25 01′N 51 04′W	1·4	3·1
22 56′N 52 45′W	1·6	2·8
20 51′N 54 30′W	1·7	7·4
18 50′N 56 16′W	1·2	5·5
Mean	1·4	4·4

The results of this series of experiments show that with a single exception the addition of nitrate and phosphate to sea water had slight effect on photosynthesis, the values obtained averaging some 40 per cent above the control. However, when nitrogen, phosphorus and iron were added the photosynthetic rate was increased by an average of 440 per cent. This value is appreciably lower than that obtained in the work described above, possibly because of the different treatment with respect to light.

DISCUSSION

Observations on an annual basis have shown that approximately $0{\cdot}5\ \mu gA/L$ $NO_3 - N$ and $0{\cdot}05\ \mu\ gA/L$ $PO_4 - P$ are always present in the surface waters of the Sargasso Sea (RILEY, 1957 ; MENZEL and RYTHER, 1960). Assuming that carbon, nitrogen and phosphorus are utilized in a ratio of 100 : 15 : 1 by atoms (REDFIELD, 1934), the average rate of plant production for the region, 3 $mgC/m^3/day$, would require the daily utilization of $\cdot 04\ \mu\ gAN/L$ and $\cdot 003\ \mu\ gAP/L$, indicating roughly a ten day supply of these nutrients at the normal rate of growth. Approaching this problem from the basis of standing crop, RILEY (1957) estimated that the level of nitrogen and phosphorus in Sargasso Sea water indicates a potential population 3 to 10 times larger than is actually measured.

The fact that these elements are never quite exhausted suggests another limiting factor. Enrichment experiments have indicated this to be iron. The influence of iron

enrichment however was only measurable in one day experiments, at which time presumably all excess available nitrogen and phosphorus was utilized. Further growth then became dependent upon the additional enrichment with nitrogen and phosphorus.

The preceding conclusions appear to be applicable to the semi-tropical and tropical Western Atlantic and indicate that previous emphasis on the importance of nitrogen and phosphorus with respect to primary production has led to an over-simplification of the general problem. It is possible that in other oceanic regions nutrients other than or in addition to, iron, nitrogen and phosphorus may become critically limiting.

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Annual variations in primary production of the Sargasso Sea off Bermuda*

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Abstract—Net and gross primary production, measured at two-week intervals over a period of three years, show annual variations during the winter period (November–April) which are directly related to the degree of mixing of the surface water and may be indirectly attributed to the severity of the winter as revealed by air temperature and wind strength. Seasonal and year-to-year changes were observed in the ratio net : gross production, as indicated by changes in the relationship between C^{14} assimilation and chlorophyll.

SINCE November, 1957 primary production has been measured at a standard oceanographic station (Station ' S ') 15 miles SE of Bermuda in the western Sargasso Sea. Measurements were made initially by means of *in situ* C^{14} experiments, since April, 1958 by a simulated *in situ* technique whereby samples from various depths are incubated on shipboard under neutral density filters which transmit the same fraction of the incident radiation as penetrates to the depths from which the samples were taken. Primary production was also determined from chlorophyll and radiation by the method of RYTHER and YENTSCH (1957), radiation having been established from KIMBALL'S (1928) tables until December, 1958, after which actual measurements were recorded at Bermuda with an Epply pyreheliometer. The annual cycle of primary production and the associated physical and chemical characteristics of the area were described for 1958 by MENZEL and RYTHER (1960), and a more detailed description of methods may be obtained from that publication. The purpose of this report will be to describe the annual cycle of primary production of the same region over two and a half years with emphasis upon variation observed during three winter periods and the conditions responsible for this variability.

C^{14} assimilation by marine plankton algae has been shown to be equivalent to net production (photosynthesis-respiration) while the plants are actively photosynthesizing (RYTHER, 1954). However, the C^{14} method, as conventionally used (cf. MENZEL and RYTHER, *loc. cit.*) includes no correction for night respiration. Only if the latter is small, relative to photosynthesis, do values approximate daily net production.

The chlorophyll-radiation method is based upon total photosynthesis and hence represents gross production, but recognized variability in the relationships between photosynthesis, radiation, and chlorophyll again preclude the possibility of any precise interpretation of the data.

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†Bermuda Biological Station. ‡Woods Hole Oceanographic Institution.

While the two methods represent the best available experimental techniques for measuring oceanic productivity, at most they provide very rough quantitative estimates of net and gross production. A more reliable application is their use in describing the relative productivity of different oceanic regions or seasonal and geographical trends within a given area. It is primarily to this end that they have been applied in this investigation. Even here, however, inconsistencies in the relationships between variables confuse the picture. The simultaneous use of the two methods serves to demonstrate, if not explain, these inconsistencies, as will be shown. Data obtained by the respective methods will be referred to for convenience, but with the reservations stated above, as net and gross production.

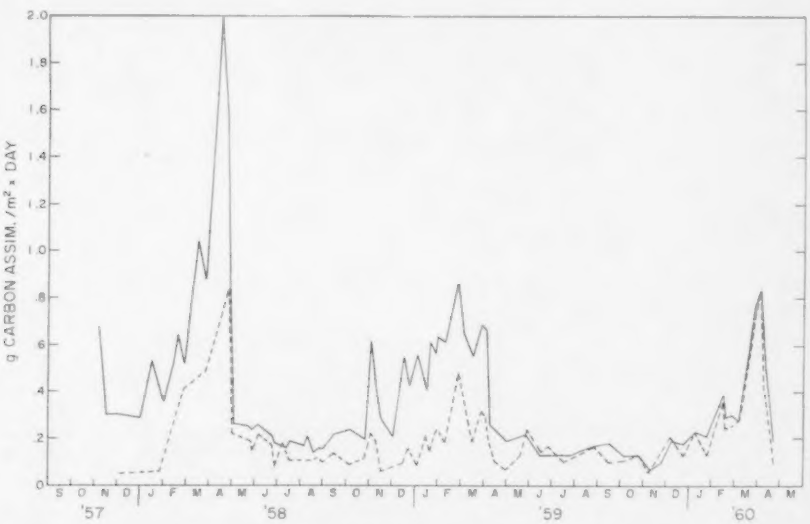

FIG. 1. Gross (solid line) and net (broken line) primary production at Station ' S,' 1957–1960.

Primary production as determined by the two above-mentioned methods from November, 1957 through April, 1960 is shown in Fig. 1. For the sake of consistency, the values obtained by the RYTHER and YENTSCH (*loc. cit.*) method have been based on radiation values taken from KIMBALL's tables throughout. As previously mentioned solar radiation was recorded daily at Bermuda after December 1958. Values for the days when productivity measurements were made are shown in Fig. 2(A) together with the monthly mean values for the Bermuda latitude from KIMBALL. The latter appear to describe satisfactorily the average radiation but, as might be expected, there were large day-to-day departures from the mean. The effect of using actual radiation data for the day in question in the RYTHER and YENTSCH calculations, as compared to values obtained by using KIMBALL's mean data, is shown in Fig. 2(B). Despite the relatively large differences in radiation and the resulting productivity calculations on individual days, the overall magnitude and seasonal trend is very nearly the same. Except where there is a need for precise photosynthesis measurements on a particular day, it would appear that the use of KIMBALL's mean values are adequate for describing productivity within the limits of accuracy of the method.

Productivity during the summers of both 1958 and 1959 was equally low and undistinguished, ranging between about 0·10 and 0·20 g carbon/m²/day by both methods and characteristic of the magnitude of production encountered wherever and whenever surface waters are strongly stratified. It is during the winter period (i.e., November–April) that the greatest production occurs and that variations from year to year become obvious. As discussed in our earlier paper, the high winter levels result from mixing to depths as great as 300 metres and the resulting enrichment of the euphotic layer. Due to the high transparency of the water (k = *ca.* 0·05) and the

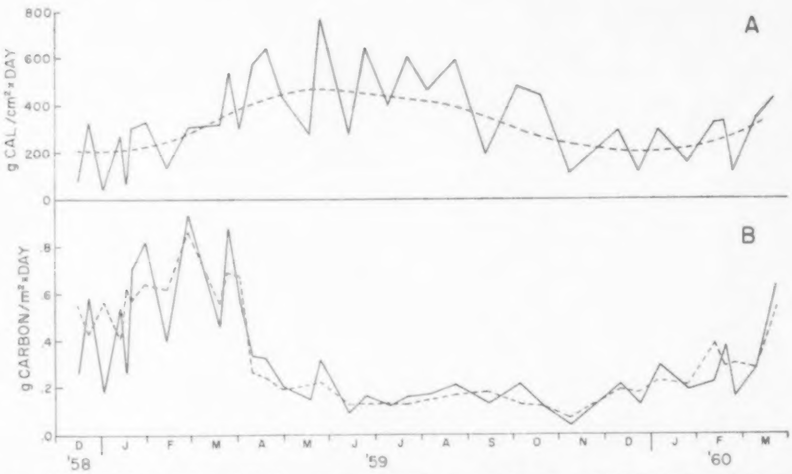

FIG. 2. (A) Incident solar radiation as measured on specific days (solid line) and from the monthly mean values of KIMBALL (1928) (broken line). (B) Gross primary production as calculated from radiation and chlorophyll by the method of RYTHER and YENTSCH (1957) using measured radiation (solid line) and KIMBALL's mean values (broken line).

relatively high incident radiation, the plants are not mixed below the ' critical depth,' the factor held responsible for low winter production further north (SVERDRUP, 1953). Annual production for the calendar years 1958 and 1959 by the chlorophyll-radiation method (gross) was 165 and 103 g carbon/m², by the C^{14} method (net), 77 and 58 g carbon/m² respectively. For the three winter periods (November–April) gross and net production, as so defined, in g carbon/m² were :

Period	*Gross*	*Net*
1957–58	127	46
1958–59	90	37
1959–60	55	46

Thus the winter gross production varied in the three-year period by almost three-fold, while net production remained nearly constant. The former is clearly correlated

with the degree of surface mixing as illustrated by the proximity to the surface of the wide band of relatively rich water of approximately 18° which overlies the permanent thermocline and underlies the seasonal thermocline (Fig. 3). In 1957–58, water of

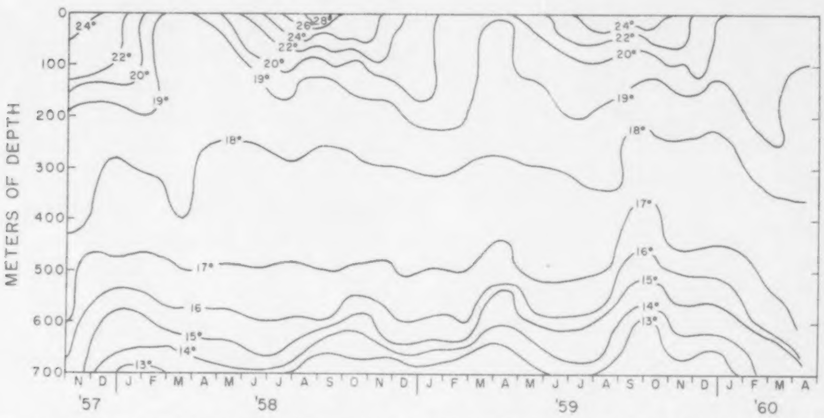

Fig. 3. Vertical profile of temperature in the upper 700 metres at Station 'S,' 1957–1960.

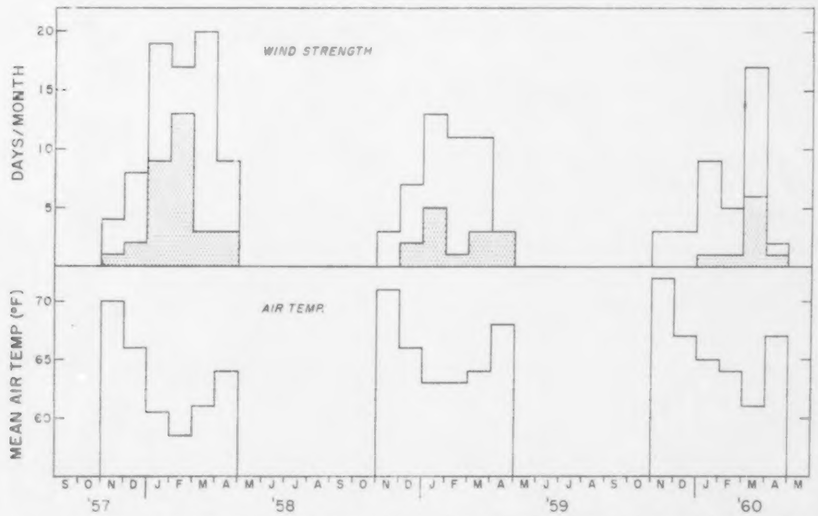

Fig. 4. Frequency of days with maximum wind strength greater than 30 knots (clear bars) and 40 knots (filled bars) and monthly mean temperatures at Bermuda from November through April, 1957–1960.

less than 19° outcropped at the surface, while in 1958–59 and 1959–60 warmer surface waters persisted throughout the winter. The mixing, in turn, appears to be directly related to the severity of the winter, as indicated by the mean air temperatures and maximum wind strengths recorded at U.S. Air Force meteorological station at Kindley Field, Bermuda (Fig. 4). The winter of 1957–58 was colder and had stronger winds than either of the two following winters. That of 1958–59, with relatively mild and uniform weather, had moderately high and uniform productivity. The winter

of 1959–60 is particularly interesting since it was initially mild with high temperatures and moderate winds, but became quite severe during March. Not until then did productivity increase to values comparable to those encountered during the previous two winters.

One of the most interesting features of the productivity measurements during the three winter periods is the lack of agreement between the chlorophyll and C^{14} methods, by more than twofold, during 1957–58 and 1958–59 and the almost perfect agreement between them from May, 1959 through April 1960. The reasons for this are not obvious. Experimental techniques have not differed significantly throughout the investigation except for the change-over from *in situ* to simulated *in situ* C^{14} measurements in April, 1958. Chemical and physical characteristics of the water were essentially the same during the three winters. Samples were taken and C^{14} experiments initiated consistently at or near midday, thereby ruling out possible diurnal influences. The species composition of the phytoplankton during 1958, a predominantly coccolithophorid flora dominated by *Coccolithus huxleyi* throughout the winter giving way to a diatom flowering in April (see Hulburt, Ryther and Guillard, 1960) was repeated almost exactly in 1959–60.

To be consistent with our interpretation of the two methods, we would have to state that net production is less than half gross production during the first two winters while the two were nearly equal in 1959–60. While there is no apparent reason for this, an examination of the relationship between C^{14} assimilation and chlorophyll will perhaps shed some light on the problem.

Each value of net production shown in Fig. 1 was obtained by integrating measurements of daily C^{14} uptake at the five depths receiving 100, 50, 25, 10 and 1 per cent of the incident radiation. Chlorophyll measurements were made at the same depths for the calculation of gross production. It is therefore possible to express daily C^{14} uptake per unit of chlorophyll for five different intensities of solar radiation each day productivity measurements were made. When this is done for a single day, a smooth curve is obtained typical of the many photosynthesis-light intensity curves in the literature. However, when these values are compared for different seasons, strikingly different curves are obtained, and the reason why productivity measurements by the two methods agree at some times and not at others becomes at once obvious.

Clearly there was a transition from low ratios of C^{14}/chlorophyll during the winter of 1958–59 through intermediate levels in the spring of 1959 to high values in the summer of 1959 (Fig. 5(A)). Precisely the same seasonal trend has been described for the North Sea by Steele and Baird (in press). It is not difficult to find reasons for this change between summer and winter with variations in temperature, radiation, nutrient levels and phytoplankton species to fall back on as possible causative factors. Steemann Nielsen and Hansen (1959), among others, have pointed out the need to modify the assimilation number (photosynthesis/chlorophyll) for different water masses, populations, etc. Ryther and Menzel (1959) have shown that failure to consider light adaptation by the photoplankton in summer may result in the under-estimation of production as calculated from chlorophyll and radiation. However, it is more difficult to explain differences in the relationship between C^{14}/chlorophyll ratio on two successive winters when physical and chemical conditions and the phytoplankton populations were essentially the same (Fig. 5(B)).

The fact that the C^{14}/chlorophyll ratio does remain almost constant for long periods of time makes it appear that the changes, when they do occur, are not simply due to technical difficulties or errors of measurement. They are undoubtedly real and probably result from some environmental variable too subtle or too complex to be obvious.

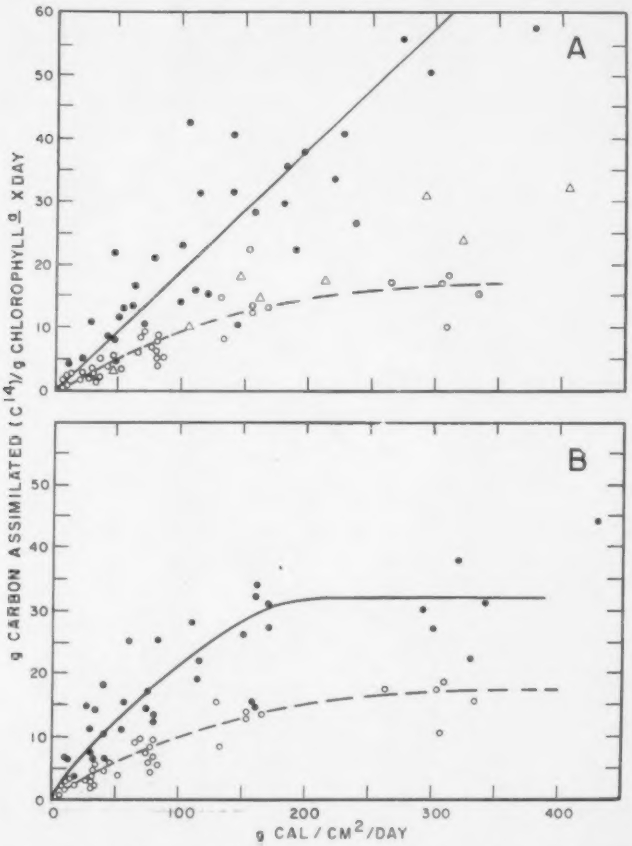

FIG. 5. (A) The ratio of C^{14} uptake/chlorophyll for different values of daily incident radiation during summer (filled circles), spring (triangles) and winter (open circles) for 1958–59. (B) The same for the winter of 1958–59 (open circles) and the winter of 1959–60 (filled circles).

We are left not only with that unanswered problem, but also with the question of whether these changes represent real differences in the relation between net and gross production or merely changes in the relationship between productivity and the criteria we have used to measure it.

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SHORT COMMUNICATION

Echo sounder records of ultrasonic sounds made by killer whales and dolphins

(*Received* 14 *September* 1960)

IT IS well known that marine mammals produce sounds in the ultrasonic frequency range (KELLOGG and KOHLER, 1952 ; KELLOGG, KOHLER and MORRIS, 1953 ; SCHEVILL and LAWRENCE, 1953 ; WORTHINGTON and SCHEVILL, 1957 ; KELLOGG, 1958) : the careful work of KELLOGG (1958) has shown that the porpoise (*Tursiops truncatus*) uses ultrasonic sound pulses as an echo ranging device.

When cruising in the tropical East Atlantic off the coast of Angola on the third expedition of R.V. *Baldaque da Silva* in 1957, ultrasonic signals were recorded seven times from dolphins (*Lagenorhyncus* sp.) and killer whales (*Orcinus orca*) on the echo sounder (Fishfinder 649·11 ; 30 kc/s ; Atlas-Werke, Bremen). On four occasions the audible component of the animals' transmissions, or clicks, were heard by the author in his cabin, at the level of the sea surface ; they may be written phonetically as hîn, hîn, hîn (dolphins) or hün, hün, hün (killer whales).

Fig. 1 shows the echo sounder record of the clicks (as a band of noise) from a large school of dolphins, of up to a hundred animals ; a few killer whales were observed at the time of the early part of the record, but there is little doubt that dense concentration of clicks was caused by the large school of dolphins ; it is possible that the abrupt departure of the dolphins was associated with the presence of killer whales. Fig. 2 shows the echo sounder record of the clicks from a typical school of four killer whales. There is a marked difference between the two records – this record and that from the dolphins. The clicks from the dolphins are very short ($< \frac{1}{2}$ m), whereas those from the killer whales are longer (1–2 m) ; again the killer whale signal is much stronger at first and fades away in signal strength towards the end of the transmission. It should be pointed out that the scale in Fig. 1 is five times that in Figs. 2, 3 and 4 ; a true comparison on the same scale can be made between Fig. 2 (killer whales) and Fig. 4 (dolphins).

The record of killer whales in Fig. 2 was not affected by the working of the MS.21 echo sounder (Kelvin and Hughes Ltd.), the working frequency of which was 10 kc/s. In contrast, Fig. 3 shows that the numbers of dolphin clicks became sharply reduced when the 10 kc/s echo sounder was switched on. The ships' officers also noticed that, on two other occasions, dolphins kept clear of the ship when the 10 kc/s sounder was running. Another interesting point about Fig. 3 is that very long 'comet' traces are found between 80 and 100 m. Traces of this type are caused by the differences in range as an object crosses the sound beam ; the greatest difference in range in these traces was from 114 m to 72 m, which means that the object crossed the beam for 176 m, making an angle of 100° over the full beam, assuming a minimum range of 72 m. At extreme angles, signals were received at a range of 114 m, which means that the object had a high coefficient of reflectivity. It would be reasonable to assume that the 'comet' traces were received from dolphins, which of course have lungs and would have a large scattering cross section. It will be noticed that the received pulse length was of constant duration for three traces, indicating that a single free swimming object was causing the signal ; the fourth, larger trace is more extensive in time at the apex of the trace. As it is of constant extent on the arms of the trace, indicating a single object, it is likely that the extensive signal at the apex is reverberation. The fact that this is possible at such a range, from a single target, reinforces the belief that these were traces from dolphins.

Dolphins working at the surface set their heads and bodies in different attitudes, as if they are scanning from side to side. Following KELLOGG's work (1958) it seems likely that they are scanning forwards with ultrasonic pulses.

Another record is shown in Fig. 4 ; there is a dense concentration of clicks received from about a hundred dolphins. They appeared on the echo record at the same time as the dolphins were sighted. The record also shows some very dense traces near the surface, which are sometimes vertically marked

and sometimes with a steep angle. It is suggested that these are echo traces of dolphins and that the ' single arm ' comet traces are caused by the animals swimming upwards or downwards ; a trace with double arms to the comet means that the target has crossed the sound beam probably at a uniform depth. In this case the target has entered the sound cone and has travelled down it and then has turned out. A hundred dolphins were present on this occasion, during one hour ten minutes in the course of four miles.

We may compare the echo records presented and in each case there is evidence of other animals, probably fish. In Fig. 1 there are sinusoidal traces within 15 m of the surface and there appears to be a thickening of trace at the surface during the time when the ' dolphin ' signals were present. In Fig. 2, there was a scattering layer near the surface and a layer at 30 m associated with a discontinuity. In Fig. 3 a few dolphins were present and a thin scattering layer near the surface. In Fig. 4, in contrast, there are dense scattering layers, concentrated ' dolphin ' clicks and possibly true echo-traces of dolphins. It is possible that the animals aggregate on patches of pelagic fish and that the denser the fish patch, the greater the aggregation of dolphins.

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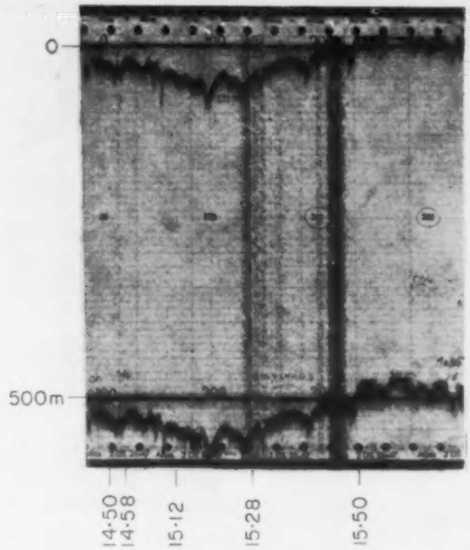

FIG. 1. An echo sounder record of the clicks from a large school (c.100) of dolphins. The following events were noticed :

1450 : a few killer whales appeared and followed the ship for about two minutes ;
1458 : a small group of ten killer whales appeared ;
1512 : some dolphin clicks were recorded, but the animals were not seen ;
1528 : about 100 dolphins were seen ;
1550 : the dolphins left the ship in a very compact school.

(Station 14 MBM *Angola* ; 26th Feb., 1957 ; 16° 35′ 7″ S., 11° 19′ 4″ E ; depth 575–475 m ; trawling 1445 hrs. to 1605 hrs. G.M.T. + 1 in direction 185° at 2·2 knots).

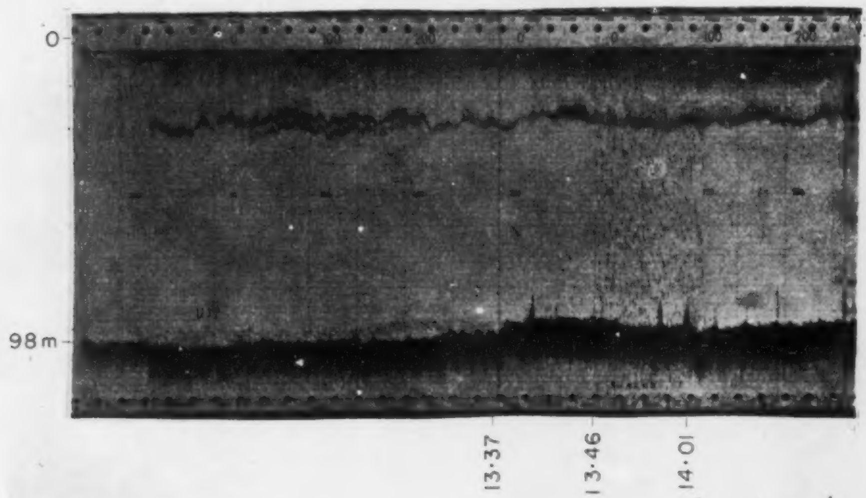

FIG. 2. A typical record of the clicks received from killer whales.

1337 hrs. : MS21 (10 kc/s) switched on ;
1346 hrs. : school of killer whales appeared ;
1401 hrs. : MS21 switched off.

(Station 17 MBM *Angola* ; 28th Feb., 1957 ; 16° 27′ 0″ S., 11° 30′ 0″ E ; depth 98–80 m , trawling 1254 hrs. to 1424 hrs. G.M.T. + 1 in direction 000° at 3·3 knots).

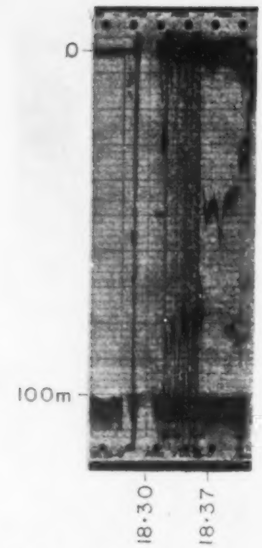

FIG. 3. A record of clicks received from dolphins ; very long 'comet' traces recorded at a range of 80–100 m. At 1830 hrs. the 30 kc/s set was switched on ; at 1837 hrs. the 10 kc/s set was switched on and the dolphins disappeared.
(Steaming 28th April, 1957 ; 12° 40′ 0″ S. ; 13° 0′ 0″ E. ; depth 150 m ; speed 8 knots).

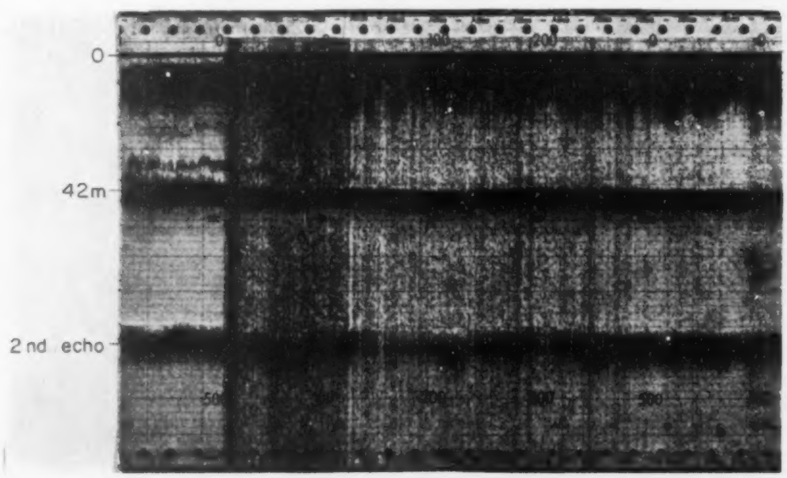

FIG. 4. A record of clicks received from a dense school of up to 100 dolphins. (Station 92 MBM *Angola* ; 18th Aug., 1957 ; 10° 38′ 1″ S. ; 13° 37′ 8″ E.; depth 42 m ; trawling 0629 hrs –0759 hrs. G.M.T. + 1 in direction 150° at 3·5 knots).

INSTRUMENTAL NOTES

A simple way of recording hydrophone depth

(*Received* 15 *October* 1960)

Abstract—A simple means of recording hydrophone depth by connection into an echo-sounding system is described. The small corrections occasionally necessary and the practical working of the system are discussed.

INTRODUCTION

MANY experiments at sea involve the use of a hydrophone, and it is usually necessary to know its depth. True depth may differ considerably from apparent depth (length of cable paid out) due to drift of the ship through the water, etc. This note describes a simple and convenient method of recording hydrophone depth by connection into a ship's standard echo-sounding system, and involves practically no new gear. To the author's knowledge it has not been used before.

Apart from estimates based on cable length and angle, hydrophone depth measurements may be split into two classes. The first depends on a pressure measurement, sometimes made directly but usually by electrical means such as a contact on a potentiometer worked by a bourdon tube. The second involves measurement of acoustic travel times. If the hydrophone transducer is reversible it can be used as a vertical echo-sounder, pinging off the sea surface. If it is not reversible a separate sound source must be provided, and there is a variety of possible types. In general the horizontal position of the hydrophone is not known and therefore a source is wanted which provides sound travelling vertically upwards, so that the time difference between the direct and surface-reflected arrival may be measured. For great water depths this condition is met by sound which has undergone one bottom reflection. With, for example, an underwater explosion source (WESTON, 1960) not only the first but several multiple reflections between surface and bottom may be heard – twelve sets were detected recently at a site 1500 fm (2743 m) deep. The structure within each arrival is simplified if a source very near the surface is used, since there are fewer distinguishable paths. The underwater explosion can meet this condition, and a charge at only a few feet depth has the added advantage that the explosion gases blow out and there are no bubble pulses to complicate the arrival pattern. Another even more convenient surface source is the noise made by a rifle bullet entering the water – three bottom echoes were detected at the same 1500 fm. site. Both these sources have been used by the author to measure hydrophone depth, but they need a special display and are really only suitable for occasional checks.

It is pointed out here that an ordinary echo-sounder projector is a very suitable near-surface source, and that the hydrophone may be connected into the ordinary echo-sounder display. The rest of this note discusses this system, but does not cover the information on hydrophone behaviour obtained whilst using it.

THE MEASUREMENT SYSTEM

The experiments were made in R.R.S. *Discovery II* in July, 1960 at a number of sites in the Mediterranean. The type 26E Kelvin-Hughes teledeltos recorder was used with the stabilized 10 kc/s magnetostriction transducers (HERDMAN, 1955). The system was tried successfully with various types of suspended receiver, typically a light barium-titanate hydrophone. By throwing a switch, the suspended hydrophone instead of the usual echo-sounder receiver, could be connected to the recorder (through an amplifier and transformer) (Figs. 1 and 2). A double trace was obtained corresponding to the direct and surface-reflected arrivals (paths 2 and 4), and the separation read off on the normal echo-sounder scale gave hydrophone depth. When possible a normal echo-sounding (path 3) was taken before each measurement (Fig. 2). It was found that the second bottom echo could also

be used to measure hydrophone depth, but there is usually no advantage in this. The direct transmission from projector to hydrophone (path 1) without intermediate bottom bounce also marked on the display and gave the slant range. Note that the echo-sounder scale reading must be multiplied by 2 here, since it is calibrated for a double path and the slant range is single path.

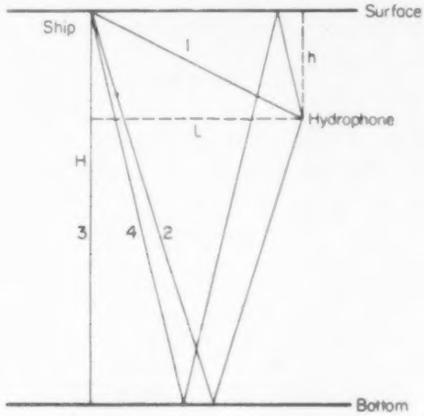

FIG. 1. Geometry for hydrophone depth measurement over flat bottom.

GEOMETRICAL CORRECTIONS

There are several small corrections which it is sometimes necessary to apply to the apparent hydrophone depth. The two most important arise because the sound arriving at the hydrophone may not be precisely vertical, making the depth reading less than the true value h. First the hydrophone may be displaced horizontally from the projector a distance l, so that the sound (paths 2 and 4 of Fig. 1) makes a mean angle θ_1 with the normal to the bottom. Secondly the bottom may slope with angle θ_2. If necessary the hydrophone depth, bottom slope etc. can be calculated exactly from measurements on paths 1, 2, 3 and 4; but some useful approximate relations are given below for the θ_1 and θ_2 effects both separate and combined.

θ_1 Effect (fig. 1). Assume $\theta_2 = 0$, $H \gg h$

$$\text{Correction factor} = \sec\theta_1 = \frac{\text{true hyd. depth } h}{\text{app. hyd. depth}} = \frac{\text{mean hyd. mark (path 2 and 4)}}{\text{water depth } H \text{ (path 3)}} \tag{1}$$

$$\text{For } \theta_1 \text{ small, } \sec\theta_1 = 1 + \tfrac{1}{2}\theta_1^2 = 1 + \frac{l^2}{8H^2} \tag{2}$$

θ_2 Effect. Assume $\theta_1 = 0$

$$\text{Correction factor} = \sec\theta_2 = \frac{\text{true hyd. depth } h}{\text{app. hyd. depth}} = \frac{\text{true water depth } H}{\text{app. water depth}} \tag{3}$$

Combined effects. Assume $H \gg h$

$$\text{Correction factor} = \sec(\theta_1 + \theta_2) = \frac{\text{true hyd. depth } h}{\text{app. hyd. depth}} \tag{4}$$

$$\text{For } \theta_1 \text{ and } \theta_2 \text{ small, } \frac{\text{true hyd. depth } h}{\text{app. hyd. depth}} = 1 + \tfrac{1}{2}(\theta_1 + \theta_2)^2 \tag{5}$$

and

$$\frac{\text{mean hyd. mark}}{\text{app. water depth}} = 1 + \tfrac{1}{2}\theta_1^2 + \theta_1\theta_2 \tag{6}$$

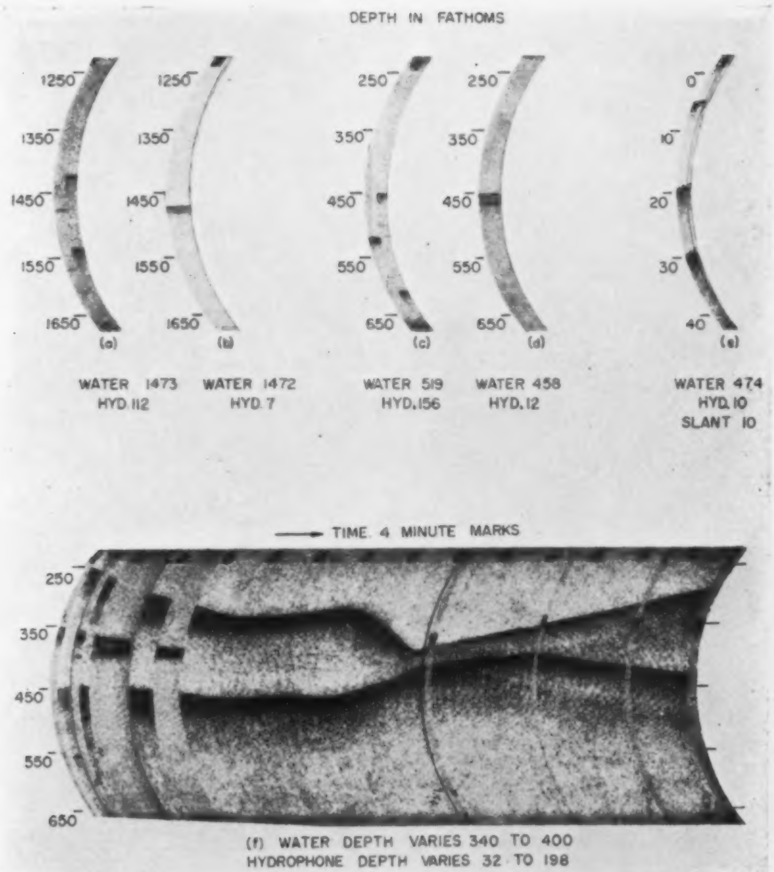

FIG. 2. Examples of hydrophone depth display on echo-sounder recorder.

If the bottom is known to be flat equation (1) shows that the correction is equal to the ratio of the mean depth at which the two hydrophone signals mark to the true water depth mark from the normal echo-sounder receiver. Equation (2) may be used to find the upper limit to the correction. During the experiments the θ_1 correction was usually negligible and never exceeded 4 per cent. Equation (3) illustrates the fact that for a sloping bottom with $\theta_1 = 0$ the corrections to hydrophone and water depth are identical. Equation (4) shows that the θ_1 and θ_2 effects can reinforce or cancel, if the bottom slopes down from the projector to the hydrophone θ_2 is defined as positive and the effects add. Equations (5) and (6) show that the combined correction cannot be reliably found by the method of equation (1). Thus the equation (6) ratio can be < 1 or > 1; whereas the equation (5) correction ratio must always be > 1, and also always greater than the equation (6) ratio. The combined θ_1 and θ_2 corrections never exceeded 10 per cent in the tests.

Over an irregular bottom there are corrections similar to those over a sloping bottom though more difficult to calculate. There may also be a small correction due to the depth of the echo-sounder projector, though this is really a correction on the equation (1) correction. Another small correction arises because of the departure of the sound velocity from the nominal value used to calibrate the recorder, also for non-vertical sound the layering will produce refraction.

PRACTICAL OPERATION OF THE METHOD

The system has been operated successfully for hydrophone depths between 4 and 200 fm in water depths between 250 and 1500 fm. There is no reason why it should not work for a much wider range of depths. The hydrophone depth marking is generally clear and often better than that for the normal receiver. The marking is occasionally poor or even unreadable over a very rough bottom when the normal echo-sounder trace is similarly affected. Though not so far observed poor results, due to surface aeration, would also be expected in rough weather or with the ship moving at speed.

Now this system obviously cannot be applied directly to measure the depth of anything which is not a hydrophone, or attached to a hydrophone and therefore needing a cable. However there are many possible variations on the acoustic travel time method, such as the use of the Edgerton pinger for monitoring bottom photography or bottom coring (Hersey, 1960). Systems with attached pingers or transponders could well be useful for depth-of-trawl indication etc.

SAMPLE RECORDS

Sample records are shown in Figs. 2 (a) to 2 (f); where there is one trace reception it is on the normal echo-sounder and where two it is on the suspended hydrophone. Fig. 2 (e) was taken with recorder speed 10 times faster than usual, and shows three traces on the same record. The first trace is the direct arrival (path 1) giving slant range, the second and third are after bottom reflection (paths 2 and 4) giving both hydrophone depth (difference) and water depth (mean) – and marking on the *third* revolution of the stylus after the transmission. Fig. 2 (d) happens to be the first record ever taken with the system. The long record in Fig. 2 (f) shows a considerable variation of hydrophone depth with time when there was 227 fm of cable out (as for (a) and (c)), and this could be tied up in detail with the ship's movements and the water streams.

CONCLUSIONS

The hydrophone depth measurement method described is simple, convenient, direct-reading, and allows continuous recording. It suffers from the same disadvantages as normal echo-sounding, for example those due to bottom roughness or slope.

Acknowledgments—This work was only made possible by the help of the Captain and Ship's Company of R.R.S. *Discovery II* and by the co-operation of several of the author's colleagues.

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An external core-retainer

(*Received* 22 *October* 1960)

For many purposes involving detailed study of the sediment-water interface (e.g. microbiological examination) it is desirable to obtain short cores in which the uppermost layers are completely undisturbed.

The corers most commonly employed with this intention (Emery and Dietz, 1941; Hvorslev and Stetson, 1946; Phleger, 1951) generally incorporate an internal core-retainer in which fingers of flexible metal or plastic are directed towards the axis of the coring tube. It has been found that such devices frequently agitate the top few centimetres of a loosely-packed or flocculent sediment, and also fail to retain sand or volcanic ash.

This note describes a device which, by replacing the conventional retainer in the above corers, facilitates the collection of undisturbed samples from a variety of sediments. Two models have been developed for use with deposits of varying consistency – one for stiffer sediments, the other for the more fluid silts or sands.

The construction and mode of operation of this apparatus are shown in the illustrations. The corer is lowered in the open position A. Penetration in excess of a pre-determined length (6 in. has been found satisfactory) forces the collar upwards, allowing the supporting arm to spring free of the catch. Upon withdrawal from the sediment the sliding weight drives the retainer down the coring tube, over the bevelled edge of the cutting head, into the closed position B. When hauled inboard the corer is held vertically, the core-retainer carefully displaced, and a tightly-fitting cork disc pushed through the cutting head into the plastic liner. The latter, with the enclosed core, is then easily removed and sealed.

This device was constructed and used aboard Lamont Geological Observatory's research vessel *Vema*, and special thanks are due to Dr. C. L. Drake for helpful suggestions towards its design and practical application.

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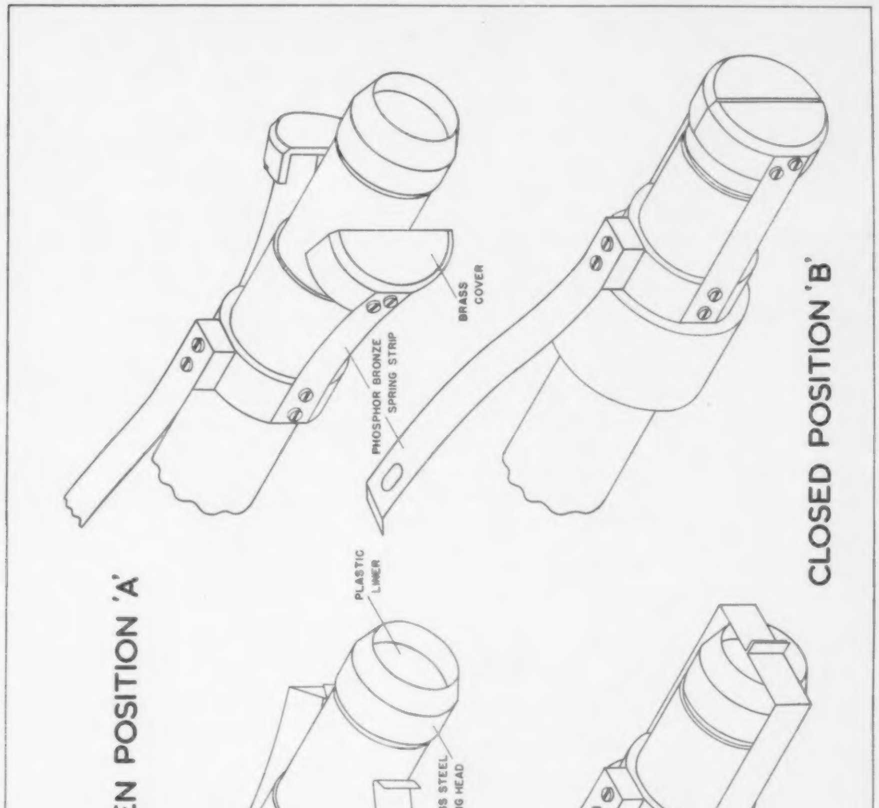
OPEN POSITION 'A'
CLOSED POSITION 'B'
PHOSPHOR BRONZE SPRING STRIP
BRASS COVER
PLASTIC LINER
STAINLESS STEEL CUTTING HEAD
BRASS TUBE
SLIDING WEIGHT
DETAIL OF CATCH
VALVE
LEAD
UNION
SLIDING WEIGHT
EXTERNAL CORE RETAINER
SECTION OF COMPLETE CORER

FIG. 1.

LETTERS TO THE EDITORS

Flow estimate for an artificial upwelling in the sea

(*Received* 4 *January*, 1961)

Abstract—An order-of-magnitude calculation of the limiting efficiency of an artificial heat source in producing a vertical oceanic current is suggested. An estimate by Groves then permits interpretation of upward flow rate of deep nutrient-rich water in terms of edible fish production rate near the surface. The latter quantity is found to be small for very large artificial heat sources.

THE SUGGESTION that a nuclear reactor placed at depth in the sea might raise convectively sufficient nutrient-rich deep water to stimulate growth of marine life in barren surface regions has been published prominently in recent months (NAS-NRC Committee on Oceanography, 1959; SPILHAUS, 1959). A means for placing this proposal in some quantitative perspective follows from an estimate by GROVES (1959) of the efficacy of Stommel's intriguing Perpetual Salt Fountain (STOMMEL, 1955).

The motion in time of water due to a point source of heat at some depth in the ocean, especially in consideration of the oceanic thermal structure, provides an interesting and difficult calculation. Irrespective of the details of this motion and the means contrived to collimate the flow, assume for the moment that the volume transfer rate of 'nutrient-rich' water from a depth d to the surface (and thus through a temperature rise ΔT) corresponds simply to the volume rate at which the given source of power can produce the appropriate temperature rise ΔT in sea water.

To understand that this assumption is a limiting case, note that water increased in temperature by less than ΔT will 'recirculate' without reaching the surface; in all cases, moreover, ineffective recirculation should occur due to entrainment of cold water and diffusion of heat about the vertical convective current. Calculation of flow rate vs. source power based on the given assumption, then tends to represent a maximally efficient system, the entire energy of which goes only to change the buoyancy of nutrient-rich water at the source depth to a state compatible with surface waters.

Actually, salinity differences between the supposed nutrient-rich and surface waters can act to make the preceding statement wrong. However, even if such salinity differences were in accord with the deep-water temperature-salinity correlation (N.D.R.C. Summary Technical Reports, 1951), maximum efficiency as estimated by the isohaline assumption would be low by less than 50 per cent. With respect to the conservative assumptions to follow and the low efficiency to be determined, variations due to salinity are judged negligible.

The source power of this idealized system is related to flow rate as follows :

$$P = r c_p \rho \, \Delta T \tag{1}$$

where P = source power

r = flow rate

c_p = specific heat, at constant pressure, of sea water $\cong$ 1 cal/g-deg

ρ = density of sea water $\cong$ 1 g/cm^3

ΔT = ambient (unperturbed) temperature rise from depth d to surface

so that the quantity

$$\frac{r \, \Delta T}{P} \cong 0{\cdot}23 \text{ cm}^3 \text{ sec}^{-1} \text{ deg watt}^{-1} \tag{2}$$

GROVES (1959) estimates edible fish production rate associated with flow rate to the surface from a depth of 300 m. His assumptions regarding inorganic nutrient concentration at this depth and its effect, when brought to the surface, upon fish population lead to a ratio of nearly 10 g of edible fish per year per cm^3 of water transferred per second.

This ratio permits replacement of transfer rate r in (2) with edible fish production rate, F, so that

$$\frac{F\,\Delta T}{P} = 2{\cdot}3\text{g edible fish yr}^{-1}\text{ watt}^{-1}\text{ deg} \tag{3}$$

Finally a representative estimate of ΔT is required. If nutrient-rich water occurred at the base of the 'isothermal' surface layer, very little power would be needed to bring it to the surface. Apparently, however, 'barren' regions occur primarily in lower latitudes (BRONNER, 1960) where the steep thermocline can extend to within 100 m or so of the surface (NDRC Summary Technical Reports, 1951). A temperature decrease of 10°C or more below surface temperature is not uncommon at depths on the order of 200 m. As an extremely conservative estimate, allowing for unknowns in the distribution of deep nutrients below barren regions, consider a value for ΔT of but one degree C.

The resultant estimate for the maximum efficacy of a thermal source, from (3), is then 2·3 grams of edible fish per year per watt of thermal power maintained at depth, or 2·3 metric tons of fish per megawatt-year.

This amount of fish is about half the haul of a small commercial fishing vessel on one 'good' day in the Santa Barbara Channel (CASTAGNOLA Brothers, 1960). Alternatively, in order to equal the California fisheries 1957 'landings and shipments' $- 7{\cdot}4 \times 10^8$ lb. (California Statistical Abstract, 1958) – about 150,000 megawatt-years, appropriately distributed against self-shielding, are indicated. For comparison, the largest nuclear reactors for which data are available provide a few hundred megawatts of thermal power.

To the extent that these assumptions have meaning even within several orders of magnitude, the preceding calculation argues strongly against the early utility of an artificial convection process for increasing the world's supply of seafood. A variety of other means are available, of course, for increasing the surface concentration of nutrients essential for marine life. These techniques can most effectively be appraised through improved knowledge of the requisite nutrients, an additional recommendation of the NAS-NRC Committee on Oceanography (1959).

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Nitrogen fixation in the Sargasso Sea

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THE stratification of surface ocean waters is normally accompanied by the depletion of plant nutrients, which are assimilated by the phytoplankton more rapidly than they are regenerated *in situ* or mixed upward from the deeper waters through the thermal gradient. In temperate and semi-tropical waters in the summer and in most tropical waters at all times, the levels of inorganic nitrogen, phosphorus, silicon and other essential nutrients are reduced to extremely low and often undetectable levels in the upper, euphotic layer.

This situation obtains in the Sargasso Sea near Bermuda from May until the seasonal thermocline breaks down in the late fall or early winter. Concentrations of combined nitrogen (nitrate plus nitrite) typically range from 0·1 to 0·5 μg A/L, phosphate-phosphorus 0·05 to 0·10 μg A/L in the upper 100 m during this period. The abundance and rate of production of phytoplankton are at minimal levels under these conditions, the latter ranging from about 0·05 to 0·10 g carbon assimilated/m^2/day, as low as has been reported anywhere in the oceans (Menzel and Ryther, 1960).

During this period of nutrient impoverishment, there characteristically appears in the surface layer a noticeably dense population of the bluegreen alga, *Trichodesmium thiebautii*, whose fusiform colonies are clearly visible to the naked eye from shipboard. Although their vertical distribution has not been investigated, the visual impression is that the organisms are largely confined to the upper one or two metres. Because of this and because the organisms are discontinuously distributed in relatively large colonies or clumps, they are seldom sampled or counted in the routine 250 ml phytoplankton samples which are taken from various depths at biweekly intervals in this area (Hulburt *et al.*, 1960).

A semi-quantitative record of the seasonal distribution of *Trichodesmium* at Station S, 15 miles SE of Bermuda, for 1960 is shown below. The data were obtained by towing a metered No. 8 plankton net at the surface for approximately 15 minutes every two weeks. The values do not give an accurate picture of quantitative distribution, but serve to illustrate the fact that the organism occurs in this region only during the summer and fall when surface temperatures are above 25° and the waters are thermally stratified.

Date	*No. colonies/m*^{3}
Before July 11	rare or absent
July 11	0·8
July 27	2·4
August 12	4·4
August 29	2·5
September 15	6·7
October 7	23·5
October 25	1·7
After October 25	rare or absent

During the winter, when *Trichodesmium* is absent at station S, conspicuous quantities of the alga were observed by the junior authors South of Bermuda where the surface waters are permanently stratified (Ryther and Menzel, 1960) and in the Caribbean Sea. Quantitative estimates were not made, but the organisms appeared to be as abundant in these southern waters in winter as in the Bermuda region in summer. In September 1960, large quantities of the alga were observed at the surface off the edge of the continental shelf as far north as 38° (R. F. Vaccaro, personal communication).

These observations are in substantial agreement with numerous reports in the literature (e.g., Cleve, 1897 ; Wille, 1904 ; and Farren, 1932) to the effect that *Trichodesmium thiebautii* is a tropical species extending its distribution into temperate waters in summer or carried northward by current systems such as the Gulf Stream. Since it occurs in quantity only when the water is thermally stratified and is nutrient-impoverished and when other phytoplankton are at their seasonal minima of abundance, the ability of *Trichodesmium* to fix atmospheric nitrogen was considered a strong possibility. Although classified as a member of the Oscillatoriaceae, in which nitrogen fixation has not previously been demonstrated, neither the taxonomy of this organism nor the ability of bluegreens as a group to fix nitrogen have been adequately studied to exclude the possibility of what would appear, from ecological considerations, to be a logical adaptation of this organism to its natural environment.

The ^{15}N method for detecting nitrogen fixation has been adapted by Dugdale, *et al.* (1959) to the measurement of nitrogen fixation rates in aquatic communities. The following procedure is carried out after placing a sample of water in a 1 litre boiling flask having a standard taper joint at the neck, and into which a specially designed gas flushing unit is fitted -

(1) atmospheric N_2 (as well as other gases) is flushed from the water with a mixture of 80/20 $He/0_2$ at a pressure of 0·8 atm ;

(2) 0·2 atm. N_2 enriched to 99·8 atom per cent ^{15}N is added to the flask and equilibrated with the aqueous phase by shaking ;
(3) the sample is incubated within the flask under the conditions selected for the experiment ;
(4) the organic fraction is converted to ammonia by micro-Kjeldahl digestion, distilled, titrated for total N and converted to N_2 with alkaline hypobromite ;
(5) the $^{15}N/^{15}N$ ratio determined with a mass spectrometer, the ratio converted to atom per cent ^{15}N, and the enrichment over the normal atom per cent ^{15}N of the organic material calculated.

Material for the experiment was collected on September 30, 1960 by towing a No. 8 plankton net at the surface. Upon return to the laboratory *Trichodesmium* colonies were selected from the net tow and inoculated into flasks containing surface seawater. One flask was enriched with phosphate, trace metals and vitamins. The flasks were incubated for 5 hours in a water-cooled box fitted with neutral density filters and placed in open sunlight (simulated *in situ* incubation). Following incubation, the particulate fraction, containing the *Trichodesmium*, was separated from the salt-water by filtration through fine-mesh parachute material, resuspended in distilled water, brought to the boil, transferred to a polyethylene bottle with 2 drops of H_2SO_2, and frozen. Subsequent analysis was carried out at the University of Pittsburgh with the following results :

% Incident (Light)	*Atom % (N15)*	*Atom % (Excess)*	*μg N (Fixed)*	*mg. N (in Sample)*
100	·372	·011	0·13	1·2
50	·367	·006	0·06	1·0
25	·364	·003	0·03	1·0
10	·363	·002	0·01	0·7
Dark	·361	·000	0·00	1·2
100 (enriched)	·361	·000	0·00	0·9
Standards	·361	—	—	—

The entire procedure has been carefully calibrated using converted ammonium sulphate as a reference standard. The least significant difference for pairs of samples at the 95 per cent confidence level is ·003 atom per cent excess ^{15}N. Two lots of untreated sample set aside to provide an initial nitrogen isotope ratio were accidentally contaminated making it necessary to discard them. However, isotope ratio determinations made at the University of Pittsburgh upon organic matter from natural waters have so far never varied significantly from that of the standards and in fact usually agree within less than ·001 atom per cent of these standards. In the absence of direct standards we are assuming that the ammonium sulphate standard represents an adequate estimate of the normal isotope ratio of the samples. The atom per cent excess ^{15}N associated with each flask has been calculated by subtracting the above value, 0·361, from the atom per cent ^{15}N found in each at the end of the experiment.

Fixation of nitrogen appears to have occured in our experiment since 3 of the 4 flasks exposed to light show a statistically significant enrichment according to the criteria described above. Furthermore, there appears to be a clear, direct relationship between the level of light during incubation and nitrogen fixation rate, with no apparent fixation in the dark. It is also interesting to note that enrichment with a mixture of phosphate, vitamins and trace minerals inhibited fixation completely. Since *Trichodesmium* was the predominant organism in the flasks, the hypothesis for nitrogen fixing ability in this alga is strengthened. Confirmation will, of course, have to await its isolation in pure culture. The results of this experiment suggest that organic production in oligotrophic tropical seas is not limited by nitrogen, a conclusion reached by REDFIELD (1958) on hypothetical grounds and in essential agreement with the experiments of MENZEL and RYTHER (in press), who found that iron is the element critically limiting plant production in the Bermuda region.

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BOOK REVIEW

FRED B PHLEGER : **Ecology and Distribution of Recent Foraminifera.** The Johns Hopkins Press, Baltimore, 1960, 297 pp. $7.50.

UM AUS fossilen marinen Sedimenten Rückschlüsse ziehen zu können über ihre Entstehung, über ihre Bildungsräume, die früheren Meere und über deren physikalisch-chemischen und biologischen Charakteristika, ist es ntowendig, die rezenten Sedimente der heutigen Ozeane eingehend zu studieren. Das Buch von PHLEGER stellt in dieser Hinsicht ein ausgezeichnetes Hilfsmittel dar, indem es einen umfassenden Überblick über die Ökologie und Verbreitung der rezenten Foraminiferen in den heutigen Ozeanen gibt.

Als Einführung werden in Kapitel I einige physikalisch-chemische Eigenschaften des Meeres, allgemeinbiologische Faktoren sowie die Faziesräume im Meer (Ästuarium, Strandsaum, Lagune, Wattengebiet, Kontinentalschelf und -abhang, Tiefsee u. a.) kurz besprochen. Anschliessend werden die Gewinnungs- und Untersuchungsmethoden rezenter Foraminiferen betrachtet.

Die Kapitel II und IV befassen sich mit den benthonischen Foraminiferen. Ausserordentlich wertvoll ist es, dass hier PHLEGER alle bisher bekannten Beobachtungen über die Tiefenverteilung der benthonischen Foraminiferenfauna zusammenfassend kritisch bearbeitet hat ; denn ohne diese Kenntnisse ist es z. B. in den heutigen Meeressedimenten nicht möglich, allochthone benthonische Foraminiferen (displaced foraminifera) von autochthonen zu trennen. Er stützt sich hierbei vor allem auf neuere Untersuchungen im Golf von Mexico, konnte dabei aber auch zahlreiche Ausarbeitungen aus anderen Meeresgebieten auswerten (siehe Fig. 13, Seite 44). Im nordwestlichen Teil des Golfes von Mexico sind Faunengrenzen für benthonische Foraminiferen erkannt worden bei ca. 100 m, bei 200 m, 600 m, 1,000 m und 2,000 m Wassertiefe. In anderen Gebieten liegen die Faunengrenzen z. T. in anderen Tiefen, so im Gebiet des nördlichen Roten Meeres bei 70, 300 und 500 m Wassertiefe. Nach den bisherigen Kenntnissen sind *weitverbreitete* Faunengrenzen vorhanden bei ca. 20 m, 50 m, 100 m, 200–300 m, 400–500 m, bei 1,000 m und 2,000 m. Eingehend bearbeitet ist auch die Tiefenverbreitung vieler benthonischer Arten. Zahlreiche Tabellen (Fig. 14–16) bringen die Tiefenverbreitung benthonischer Arten aus dem Schelfgebiet vor der Texasküste, aus dem nördlichen Golf von Mexico, vom atlantischen Schelf zwischen Gulf of Maine und Maryland u. a. Dabei konnte oft bei einzelnen Arten die Verbreitung lebender und toter Exemplare getrennt dargestellt werden. Anschliessend daran werden die Einflüsse diskutiert, die die physikalisch-chemischen Eigenschaften (Temperatur, Salzgehalt u. a.) und die Nährstoffverhältnisse des Meerwassers auf die Verbreitung der benthonischen Foraminiferen ausüben. Weitere Untersuchungen werden hier zweifellos noch viele neue wichtige Erkenntnisse bringen.

In Kapitel III werden die benthonischen Faunengemeinschaften in den verschiedenen Faziesgebieten der heutigen Meeresräume besprochen. Hier konnten nicht nur Arbeiten aus dem amerikanischen Meeresgebiet ausgewertet werden, sondern auch Veröffentlichungen aus europäischen und asiatischen Meeren. Diese kritische Untersuchung der benthonischen Fauna in Lagunen, in Wattengebieten, in Strandzonen, im Bereich von Korallenriffen u. a. sind nicht nur zum Verständnis der heutigen marinen Sedimente bedeutungsvoll, sondern sie sind auch eine ausgezeichnete Hilfe für die Geologen, die Faziesräume in fossilen Sedimenten auf Grund der Foraminiferenfauna auszuscheiden haben.

Die bisherigen Studien über die Verbreitung von lebenden benthonischen Foraminiferen (Kapitel IV) zeigen, dass im grossen und ganzen die Lebensgemeinschaft (Biozönose) und die Totengemeinschaft (Thanatozönose) der benthonischen Foraminiferen übereinstimmen ; d. h. eine starke Verfrachtung der leeren Schalen benthonischer Foraminiferen findet im allgemeinen nicht statt. Die Bevölkerungsdichte lebender benthonischer Foraminiferen pro m^3 Meeresboden kann stark schwanken ; im Gulf of Maine sind im Durchschnitt 3,000 Exemplare pro m^3, im Gebiet des Mississippi-Deltas 90,000 pro m^3, im küstenferneren Schelfgebiet des nordwestlichen Golfes von Mexico dagegen nur 10,000 Exemplare festgestellt worden. Die Anzahl lebender benthonischer Foraminiferen auf

dem Meeresboden ist stark abhängig vom Nährstoffgehalt des Meerwassers. Dies zeigt deutlich die Beobachtung in der Todos Santos Bay, Baja California ; in den Monaten Juni und August nimmt hier die Bevölkerung benthonischer Foraminiferen stark zu, da zu diesen Zeiten die Hauptentwicklung der Diatomeen liegt, die vorwiegend den Foraminiferen als Nahrung dienen.

In den Tiefseesedimenten stellen die planktonischen Foraminiferen meistens die wichtigste biogene Komponente dar (Kapitel V). Sie leben vorwiegend im Oberflächenwasser der Ozeane. Nur die Kalkschalen abgestorbener pelagischer Foraminiferen finden sich zusammen mit lebenden und abgestorbenen benthonischen Arten im Meeressediment wieder. Benthonische und pelagische rezente Foraminiferen sind daher getrennt zu behandeln. Um die Totengemeinschaft pelagischer Foraminiferen auf dem Meeresboden deuten zu können, muss die Verbreitung der pelagischen Arten im Wasserraum möglichst in grossen Zügen bekannt sein. Dies ist in dem nördlichen, dem äquatorialen und südöstlichen Pazifischen Ozean der Fall, desgleichen in den wesentlichen Zügen in verschiedenen Gebieten des nördlichen und äquatorialen Atlantischen Ozeans sowie im Golf von Mexico. Da im nördlichen und äquatorialen Pazifischen Ozean Material von über 700 Plankton-Netzfängen zur Verfügung stand, konnten hier entsprechend den Temperaturverhältnissen des Oberflächenwassers 4 Faunengemeinschaften ausgeschieden werden (subarctic fauna, transition fauna, central fauna, equatorial west-central fauna). Die vertikale Verbreitung der pelagischen Arten innerhalb der oberen Wasserschichten des Ozeans ist noch nicht ganz geklärt. Nach Untersuchungen im Mittelländischen Meer scheint *Orbulina universa* d'Orbigny zwischen 50 und ca. 300 m Wassertiefe auf- und abzusteigen.

Auf dem heutigen Meeresboden des Nordatlantischen Ozeans einschliesslich des Golfes von Mexico ist durch quantitative Untersuchung die Verbreitung der Schalen abgestorbener pelagischer Foraminiferen verhältnismässig gut bekannt und auch deutbar. Hier sind genauso wie neuerdings im Wasserraum des Pazifischen Ozeans seit längerem mehrere Faunengemeinschaften beobachtet worden, deren Verbreitung vor allem von der Temperatur des Oberflächenwassers abhängig ist. In den aus dem Meeresboden gewonnenen Sedimentkernen liegen häufig mehrere Faunengemeinschaften in vertikaler Richtung übereinander. Diese Faunenänderungen in vertikaler Richtung bilden die Grundlage für eine biostratigrapische Gliederung der rezenten Meeressedimente. Im letzten Kapitel (VI) werden z. T. in Form einer zusammenfassenden Übersicht aus den gewonnenen Erkenntnissen die wichtigsten Schlussfolgerungen gezogen, die für die Untersuchung rezenter und auch fossiler Sedimente von Bedeutung sind.

Dieses Buch ist für Geologen und Ozeanographen, so wie es Phleger im Vorwort gehofft hat, nicht nur wertvoll, sondern unentbehrlich bei Arbeiten auf dem Gebiete der marinen Geologie.

W. Schott

NEWS AND NOTES

Dr. K. M. Rae, formerly officer-in-charge, Oceanographic Laboratory, Edinburgh, Scottish Marine Biological Association, 1950-1957, has been appointed director of the Marine Laboratory, University of Alaska. He is presently director of the Marine laboratories and professor of biological oceanography at the Agricultural and Mechanical College of Texas and also editor of *Limnology and Oceanography*.

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